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Development and Demonstration of Concepts for Improving Coke-Oven Door Seals

Battelle Columbus Labs, OH

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Development and Demonstration of Concepts for Improving Coke-oven Door Seals:
Interim Report

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EXECUTIVE SUMMARY

ORIGIN

In 1974 the Industrial Environmental Research Laboratory of EPA and the American Iron and Steel Institute (AISI) reached an agreement to fund a program for a phased technical study to decrease/eliminate visible emissions from coke-oven door seals on *existing* ovens. The phases or projects of the program were:

I. Study of Concepts for Minimizing Emissions from Coke-Oven Door Seals

II. Development of Concepts for Improving Coke-Oven Door Seals

III. Demonstration of Concepts for Improving Coke-Oven Door Seals

In competitive bidding, Battelle-Columbus Laboratories was awarded a jointly funded research contract dealing with Phase I. This project was completed in July of 1975.* The conclusions of the Phase I project were:

- Of all of the concepts considered, upgraded metal seals have the best potential for meeting all of the emission control and retrofit criteria
- The entire end closure should be analyzed quantitatively because the dimensional instability of the jamb and other components is part of the leakage problem
- Variations of luted seals should be evaluated in a laboratory arrangement to obtain information on their potential for successful development, acceptance, and implementation.

THIS PROJECT

In August of 1976, Battelle-Columbus was awarded research contracts (with EPA and AISI) dealing with Phase II of the program, i.e., the research/development aspects of the conclusions and recommendations of the concepts study.

The specific objective of this project was to "innovate and to develop at least one new system that will be proven in the field to be retrofittable to existing coke ovens, mechanically and physically suitable for commercial use in steel plants, and highly effective in containing and controlling emissions from the ends of ovens". The effort was broadened from improved seals alone to research consideration of all components of end closures, i.e., "from the bricks out".

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*The report on this project was entitled "Study of Concepts for Minimizing Emissions from Coke-Oven Door Seals". It may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161. The report number is PB 245580.

THIS REPORT

This particular development project was organized into six interrelated tasks. The first three tasks were conducted concurrently and were entitled:

1. Mathematical Modeling and Analysis of Systems
2. Physical Modeling and Laboratory Experimentation
3. Field Data Collection and Field Experimentation

These first tasks were reported to the sponsors in the form of working paper summaries.

These were followed by Task 4 which is entitled "Analysis, Evaluations, and Recommendations". *This report is the summary of our evaluations and recommendations resulting from Task 4.*

While this report was being critiqued by the sponsors, work was in progress on Task 5 ("Full-Scale Unit Design and Testing of Parts"). Contractual arrangements allow the sponsors to exercise an option of funding Phase III (the demonstration phase) without any lost time between projects. For this possibility, Task 6 ("Decisions Regarding Full-Scale Installations") is being completed concurrently with Task 5.

MAJOR CONCLUSIONS AND RECOMMENDATIONS OF THIS PHASE II PROJECT

1. Battelle's recommended, retrofittable door-seal system has the following elements:

   - A preferred new design of seal (page II-23)*
   - Use of high-strength, heat-resistant materials (page II-37)
   - Special considerations regarding seal adjustment/attachment (page II-29).

   It is judged that the recommended door-seal system will be applicable to 4 to 6-meter batteries.

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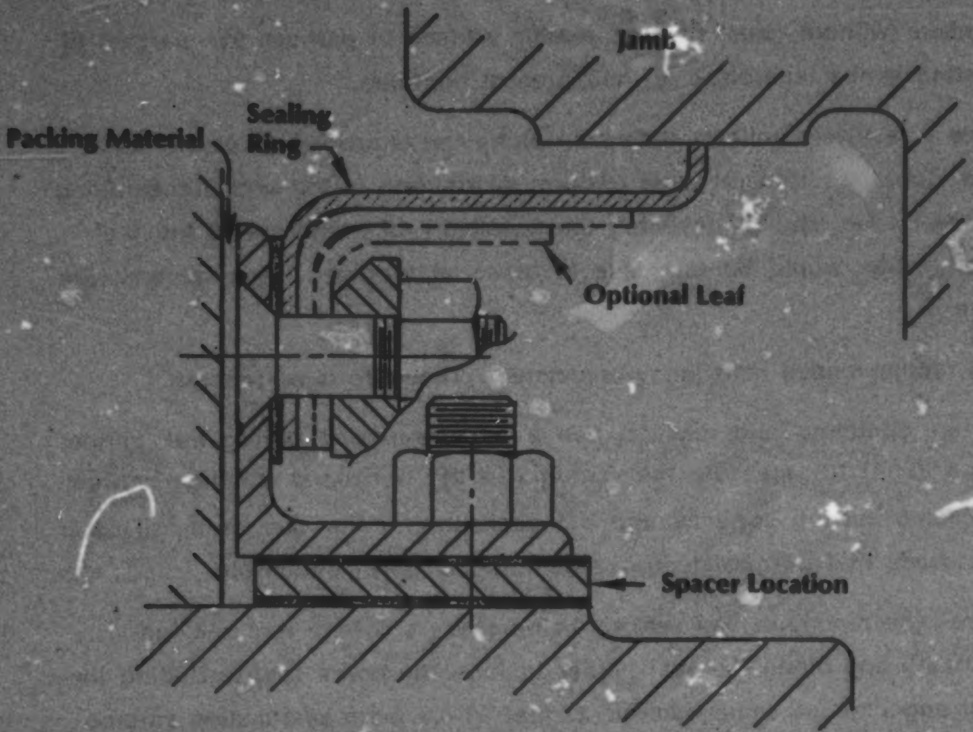
*The numbers in parentheses refer to page numbers in this report.

The recommended design of metal-to-metal seal is shown in cross section as follows:



In our judgment, this simple design, fabricated from high-performance material will:

a. Flexibly absorb the latching force without recourse to additional localized or point-applied forces. Point-loading of the seal has been eliminated to help equalize the distribution of loading along the seal.

b. Minimize stress-concentration problems at the corners of the seals.

c. Have an elastic seal-edge flexibility (allowable displacement) 2 to 3 times higher than existing S-shaped seals. Inconel X-750 and other alloys will be tested in Task 5 for this application.

d. Be adaptable as a single design to both Koppers and Wilputte designs for doors.

e. Have a longer good-performance life than standard seals. The use of harder and tougher materials will lower the sensitivity to physical damage.

By a special procedure for attachment and adjustment, the recommended seal can (we believe) be made to:

- Contact (without gaps) the seal-mating surface of perhaps 90+ percent of existing jambs regardless of their present contours.*
- Have a relatively uniform deflection along the entire length of the seal. This would result in (a) more uniform distribution of the latch forces along the seal edge, and (b) lowering the possibility of overstressing the seal. Both results would be favorable in terms of long-life, improved emission control.

The recommended installation/adjustment procedure is as follows:

a. At an operating end closure, use a tool developed during this project (page II-14) to measure the variation in the horizontal distance between the jamb sealing surfaces and the backsides of the door frame. This is the space that the seal has to accommodate (seal) effectively.

b. Install the recommended seal by using spacers (where required) underneath and along the seal holder to form the *entire* seal (including the seal edge) to the same contour as that of the jamb seal-mating surface. The amount of spacing is set (within workable tolerances) by the measurements obtained at the operating oven.

This procedure may custom fit a door to only one jamb. However, it is expected that the same door and seal will fit several jambs on the same battery because of the tendency for jambs on a battery to assume similar contours.*

One setting of the spacers is expected to give satisfactory performance for some long period of time. Part of this expectation is based on the increased flexural tolerance designed into the seal. Mechanical-screw adjustments were considered for moving the entire seal to obtain conformity with the jamb, but design of this variation was held in abeyance because of (a) the high cost of this variation, and (b) the concern that manual adjustment can result in overstressing (warping) of the seal.

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*The actual limitations (if any) are to be established in the demonstration phase.

2. There may be some existing jambs that are distorted to the point where they cannot be fully contacted (no gaps) by any metal seal without developing distortions in the seal itself. In these instances, it is recommended that new jambs be installed. Our analysis/judgment indicates that these jambs and those on all new batteries and rebuilds should:

   - Be installed so that they are in a state of low or zero thermal stress when in their operating-temperature range
   - Have a short web depth to lower both the stiffness of the jamb and the temperature gradient that occurs during transient thermal flux conditions
   - Be castings made of ferritic ductile iron castings
   - Be locked in place to prevent hourglassing and thermal flexing.

   A low thermal stress state occurs when the jamb has been allowed to or encouraged to bow inward (top and bottom out from the oven) to relieve the stress generated by the normal temperature differential across the jambs. In the thermally bowed "natural" condition, jambs will develop less stress when they are heated or cooled (rain storms) outside of the normal operating temperature range. Lower stress will translate to less distortion and, therefore, to longer jamb life. During this project, it was learned that one coke-plant builder adopted the concept of "naturally bowed jambs" several years ago. Also, the technical personnel of one coke plant had come to the same conclusion regarding the advantages of a shorter web depth, and have machined their jambs accordingly.

3. Our research efforts dealing with various ways to use sealants developed into an evaluation of what we have termed "inboard luting". In this instance, improved luting material (clay-based mixtures) is mechanically placed into the gas passage of existing metal seals while the door is off the oven. Sealing occurs when the water-tempered luting material is compressed by latching the door. Luting material would have to be applied for every coking cycle.

   It was concluded that:

   - If inboard luting could be fully developed and implemented it has the potential of being a sealing method that is both smoke-tight and gas-tight through the entire coal-charging and coke-making cycle. It has this potential because coal tars and liquids seal the pores of the luting material as it dries.

- The inboard luting method is not sensitive to the condition of the jambs or door seals. It could be used where end closures are in "bad" condition.
- The cost of material for inboard luting is low, but the overall cost is expected to be appreciably higher than for the retrofittable metal seal if additional workers must be hired to operate the sealant-application equipment.

It is recommended that the coke-producing industry (producers of blast furnace coke and foundry coke) be polled to determine whether there is enough interest in the inboard-luting approach to underwrite a development and implementation effort. Inboard luting may be attractive in situations where the battery age does not justify the expenditure for new end-closure components. The possibility exists that inboard luting will eliminate the need for manual cleaning of jambs and doors. If this proves to be correct, then luting may at some locations be substituted for the cleaning operation with no increase in crew size.

4. The recommended metal-to-metal sealing system should be evaluated in a demonstration project on operating coke-oven batteries. As part of this demonstration, a number of closures incorporating the recommended system should be compared with a number of closures incorporating new-component standard designs and possible competing designs.

Comparisons should be made in terms of:

- Emission-control effectiveness
- Level of attention required to maintain an acceptable seal
- Life of the system in terms of acceptable emission control
- Overall costs, including original installation and repair and adjustment operations
- Operator acceptance.

The demonstration project may be too short to obtain data on the very important cost-per-year basis, but it would be expected that some indications may develop in a year's time. Continued evaluation by coke-producing companies, after the end of the demonstration project, should develop long-term cost information.

As part of the technology transfer effort, there will be a requirement for considerable technical and evaluation input by steel-company personnel at the host plants.

CHAPTER I

INTRODUCTION

This report summarizes Task IV (Analysis, Evaluations, and Recommendations) of a research project entitled "Development and Demonstration of Concepts for Improving Coke Oven Door Seals". This report is being issued after 20 months of effort in a 24-month development project. The main objectives of releasing this report prior to the completion of the project are to:

(a) Formally present our conclusions before completion of the project

(b) Present our recommendations dealing with additional effort on this present project and a following demonstration project that is under consideration

(c) Obtain permission from the Sponsors to proceed with the remaining Tasks in this project

(d) Make it possible for the Sponsors to make plans for going into a follow-on demonstration project without interruption in the overall program.

The work reported herein was sponsored by the Industrial Environmental Research Laboratory of the EPA and by the American Iron and Steel Institute (AISI). The opinions, evaluations, judgments, and recommendations expressed are strictly those of the participating Battelle-Columbus staff.

Background and Antecedents

In January of 1970, Battelle-Columbus issued a formal report on coke-plant emissions control to the National Air Pollution Control Administration.* In that report, Battelle researchers recommended that the solution to air-emissions problems, which all coke-oven operators have in common, can "best be achieved" by group action and joint contributions. This recommendation was particularly appropriate for emission-control problems having complex technical components and involving unknown and/or conflicting factors and opinions. The term "best be achieved" takes into consideration the favorable odds involved in an adequately funded, objective, cooperative, and well-publicized technical approach, as compared with uncoordinated empirical approaches. In this regard, we hasten to say that empirical approaches can be successful provided that motivation is high and sufficient time is allocated to the problem. This present project (and a preceding project) are examples of combined effort towards a common goal.

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*Evaluation of Process Alternatives to Improve Control of Air Pollution from Production of Coke". Prepared for the Division of Process Control Engineering, National Air Pollution Control Administration under Contract PH 22-68-65. Available from the National Technical Information Service as Document PB 189266.

In January of 1974, the Battelle-Columbus Laboratories responded to an EPA Request for Proposal (EPA RFP No. DU 74-A039) dealing with a research project to study, innovate, and evaluate *concepts* for minimizing emissions from coke-oven door seals. It was understood that the research would be sponsored and financed jointly by EPA and the AISI and that the research was to be monitored by EPA.

After competitive bidding, the contract for this research project was awarded to Battelle-Columbus in June 1974. This research project followed the plan outlined in the RFP and was entitled "Study of Concepts for Minimizing Emissions from Coke-Oven Door Seals". The approved final report was issued in July of 1975. Copies of this report are available from the National Technical Information Service (NTIS) as Document PB 245580.* This report is reference material for the present project.

In January of 1976, Battelle-Columbus was asked by the EPA/AISI (EPA RFP No. DU-76-A103) to present a proposal and a series of recommendations dealing with "Development and Demonstration of Concepts for Improving Coke-Oven Door Seals". This proposal was to be based on the conclusions and recommendations of the July 1975 Concepts Study. As given above, the title of the possible new project was somewhat of an understatement because the Sponsors were interested in research and development of all aspects of end closures that relate directly or indirectly to emission control. Battelle-Columbus presented a proposal that was responsive to the following points:

(a) Follows through and develops further the conclusions and recommendations of the Concepts report.

(b) Schedules arrangements to present our results and recommendations for the Phase III demonstration prior to the end of the project (as in this report) for critique by the EPA, members of the AISI and their research organizations, and other interested organizations. This critique period allows time for evaluation by the Sponsors as to whether the follow-on demonstration project should be funded, and allows continuation of the overall program without interruptions between major phases.

(c) Takes into consideration and makes use of the end-closure and emission-control data to be supplied by several large steel company research laboratories. Battelle researchers were also to obtain measurement data, but were to make independent conclusions and recommendations.

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*The address of the NTIS is 5285 Port Royal Road, Springfield, Virginia 22161.

(d) Defers plant testing of recommended seals, jambs, doors, and other end-closure components until given technical and administrative clearance by EPA and AISI to do so.

Our proposal was accepted and a contract was awarded in August of 1976. The development work, including engineering drawings of our proposed designs, will be completed by the end of August, 1978.

Project Objectives

The objectives as stated in the contracts with EPA and AISI are as follows:

> The general objective is to innovate and to develop at least one new system that will be proven in the field (in an optional follow-on project) to be retrofittable to existing coke ovens, mechanically and physically suitable for commercial use in steel plants, and highly effective in containing and controlling emissions from the ends of ovens.
>
> The primary objective is to develop a retrofittable metal-contact seal that (a) is more flexible in terms of conforming to large distortions of jambs, (b) is more heat resistant than existing seals, and (c) will conform to warped jambs without the need for periodic adjustments by coke-plant workers.
>
> The end-closure system also includes the jamb (along with the mounting of the jamb and other considerations). Because the warpage of jambs is the fundamental cause of the emission-releasing gaps between the jamb and the seal, it is a second objective of this project to develop a more dimensionally stable jamb for both new coke-oven batteries and for replacement of some jambs at existing batteries.
>
> It is a third objective to develop a bank of quantitative information that describes the conditions and variables that affect the performance, effectiveness, and life of coke-oven end closures. Analysis of the technical results and the quantitative information obtained should result not only in an effective solution to the problem, but also pinpoint *why* it is effective and what needs to be done in the field to maintain effectiveness.
>
> A fourth objective is to explore the potential of systems using sealants. In Contract No. 68-02-1439, "A Study of Concepts for Minimizing Emissions From Coke Oven Seals", a number of unknowns surfaced in the subjective evaluations of conceptualized sealant systems. Sealing via the use of sealants is included for study in a laboratory research program to evaluate the potential applicability to the general objective.

Organization of the Project

The overall development project was divided into six tasks as shown in Figures I-1 and I-2. This report, for example, is the Interim Report listed as Task 4 in the following figures. The Optional Tasks shown are part of a possible follow-on demonstration project, with implementation at the option of the Sponsors.

Our approach was to carry out the first three interrelated tasks concurrently. The titles of these tasks are as follows:

Task 1: Mathematical Modeling and Analysis of End-Closure Systems (Seals, Jambs, and Doors)

Task 2: Physical Modeling and Laboratory Experimentation

Task 3: Field Data Collection and Field Experimentation

As a general statement, the data collected in Task 3 were used as inputs to Task 1 and Task 2. The analytical results of Task 1 were verified in Task 2.

Tasks 1, 2, and 3 were conducted on an accelerated basis over a period of 16 months. The completion of Tasks 1, 2, and 3 was followed by Task 4 which is entitled "Analysis, Evaluation, and Recommendations". This is a 3-month task which is summarized in this interim report. The recommendations of Task 4 will be implemented in Task 5, which is entitled "Full-Scale Unit Design and Testing of Parts". "Testing of parts" anticipated a need to study the sealing (and bending) action of sections (and corners) of recommended, retrofittable seal design(s)/materials.

The last task in this project is Task 6: "Decisions Regarding Full-Scale Installations". This 2-month task represents a period of interaction with the representatives of the Sponsors involving decisions required to initiate or define the Optional Scope of Work (a demonstration project).

The general timing of the project, and the timing of the tasks within the project, are shown in Figure I-2. Also shown is the timing of the Optional Project. Overall, the timing of the basic project has been scheduled as short as possible so as to find, as rapidly as possible, an acceptable solution to an air-pollution problem.

Research Staff

This research is being conducted by coordinating the efforts of researchers within three Departments at Battelle:

(1) Metallurgy Department
(2) Structures and Mechanics Research Department
(3) Engineering and Manufacturing Technology Department.

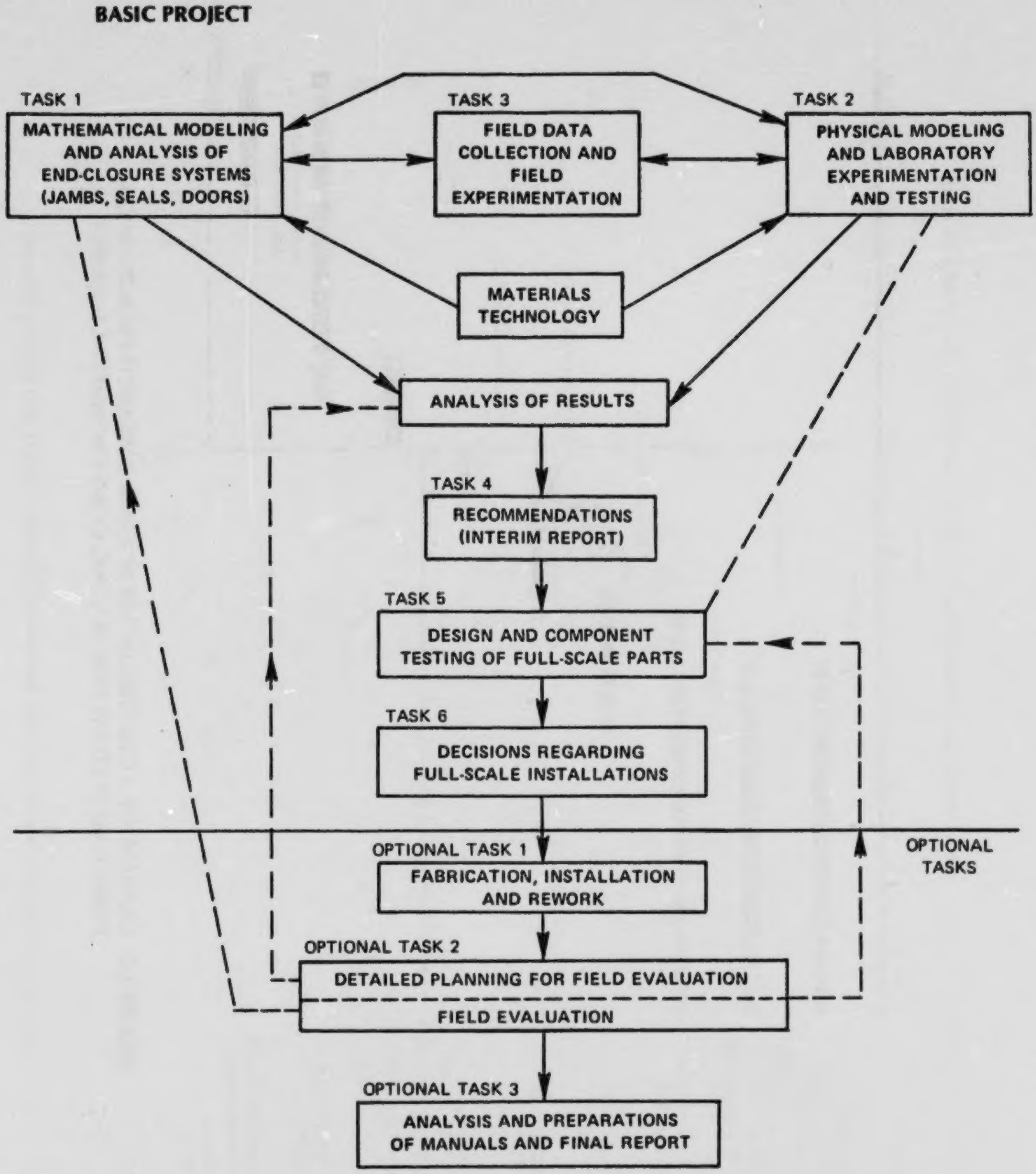
BASIC PROJECT
TASK 1
MATHEMATICAL MODELING AND ANALYSIS OF END-CLOSURE SYSTEMS (JAMBS, SEALS, DOORS)
TASK 3
FIELD DATA COLLECTION AND FIELD EXPERIMENTATION
TASK 2
PHYSICAL MODELING AND LABORATORY EXPERIMENTATION AND TESTING
MATERIALS TECHNOLOGY
ANALYSIS OF RESULTS
TASK 4
RECOMMENDATIONS (INTERIM REPORT)
TASK 5
DESIGN AND COMPONENT TESTING OF FULL-SCALE PARTS
TASK 6
DECISIONS REGARDING FULL-SCALE INSTALLATIONS
OPTIONAL TASKS
OPTIONAL TASK 1
FABRICATION, INSTALLATION AND REWORK
OPTIONAL TASK 2
DETAILED PLANNING FOR FIELD EVALUATION
FIELD EVALUATION
OPTIONAL TASK 3
ANALYSIS AND PREPARATIONS OF MANUALS AND FINAL REPORT

FIGURE I-1. OUTLINE OF TASKS IN THE BASIC AND OPTIONAL PROGRAM AND SCHEDULE OF SUMMARIES AND REPORTS

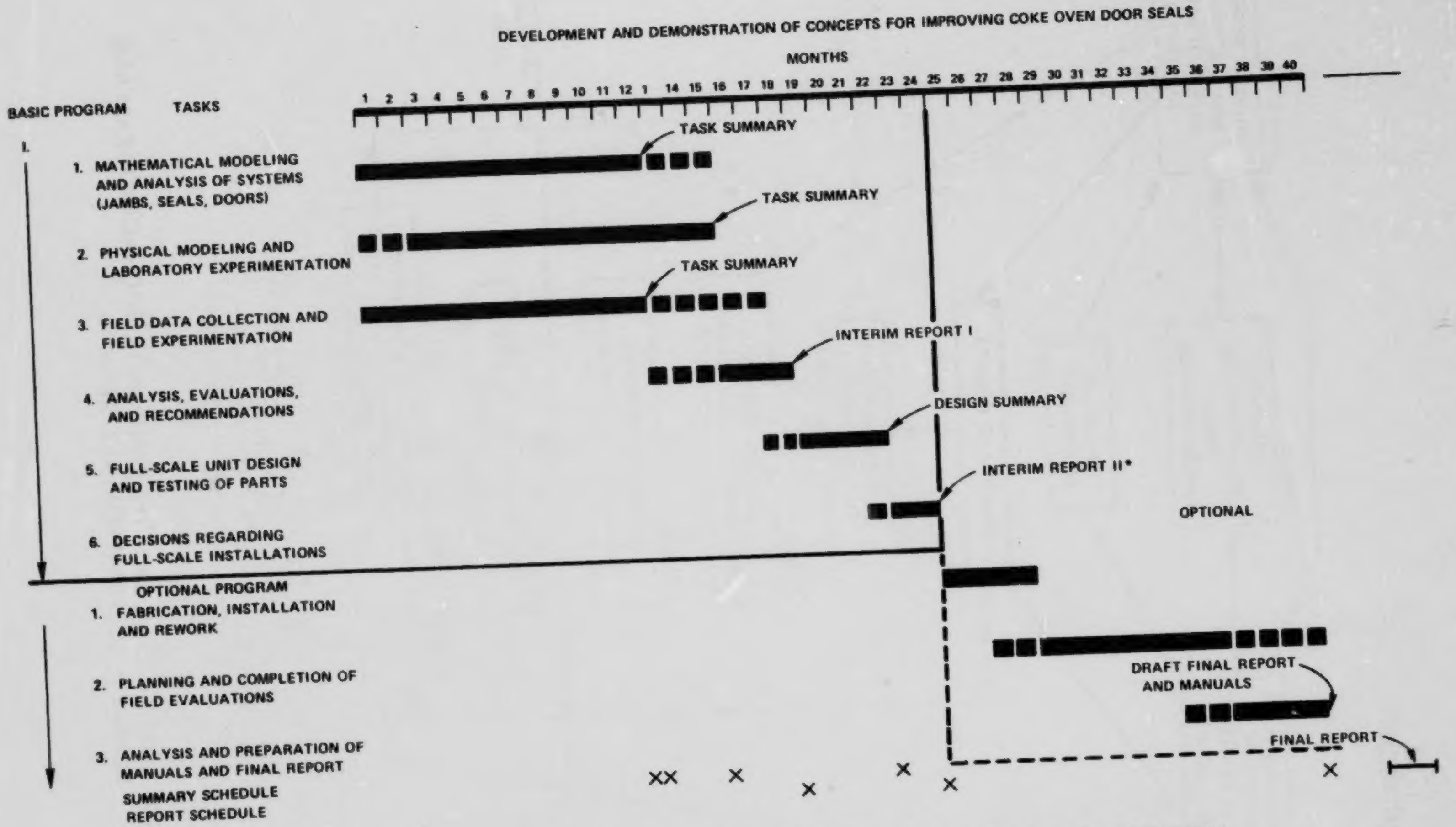

FIGURE I-2. OUTLINE OF ACTIVITIES IN THE EPA/AISI RESEARCH PROGRAM ON IMPROVED SYSTEMS FOR SEALING COKE-OVEN END CLOSURES

*This report becomes a Final Report if the Sponsors do not elect to fund the Optional Program.

The key or lead personnel within the three departments are as follows:

A. O. Hoffman, Project Manager, Metallurgy Department
H. W. Lownie, Technical Advisor, Metallurgy Department
A. T. Hopper, Leader of the analytical effort, Structures and Mechanics Department
R. L. Paul, Leader of the design effort, Engineering and Manufacturing Technology.

The Sponsorship personnel most directly concerned with this study are:

Mr. Robert C. McCrillis, Project Officer for EPA
Mr. John G. Munson Jr., Project Officer for AISI (now retired)
Mr. Richard G. Phelps, Project Officer for AISI
Mr. Calvin Cooley, AISI Headquarters, Washington, D.C.
Mr. George C. Bennett, Contract Administrator for EPA
Mr. M. P. Huneycutt, Contracting Officer for EPA.

Acknowledgments

Having the support of the AISI on this project was advantageous to Battelle researchers working on this project. This was particularly evident during our plant visits and field-test periods. During this and the prior project, Battelle researchers could have probably visited and worked at any coke plant in North America. For the support of the AISI and the input of *many* coke-plant personnel, we wish to give acknowledgment.

We give special acknowledgment to (a) the assistance given to us at each of the coke plants where we elected to obtain detailed measurements, and (b) to the United States Steel Corporation research organization for furnishing their internal technical report entitled "Coke Oven-Door System Technology: Field Data From Clairton Works" (December 1976). We are fortunate in being able to quote from this report and in this manner are able to acknowledge the technical contribution of the United States Steel Corporation to this AISI project. While several steel companies gave us permission to examine their internal reports, the formal and detailed USS report had a significant impact on our insights into the problem.*

In our field work there were many examples of concern for our safety and well being. These are particularly appreciated. In one instance, an Assistant Plant Superintendent came to us where we were working on the bench, handed us his personal snow shovel, and ejected us from the plant. His objective was to minimize explanation time and get us out before the blizzard hit. His action saved us from being snow bound with him for several days or longer. During our "retreat" we had to use his snow shovel even before we had driven to the plant limits.

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*The United States Steel Corporation has asked that requests for this USS report be directed to them.

We would have liked to give acknowledgment to all individuals who gave the project team assistance on this project but ran into a problem with "where do we stop the list?"

Project Manager's Comments and Qualifying Statements

(1) Two important considerations in our research project are (a) maximum retrofittability and (b) minimum visible emission from the end-closure system. The retrofittability aspect limited the range of modifications that could be considered. Our recommendations, therefore, may or may not be appropriate for the taller ovens of the future. It is hoped, however, that our effort will be helpful in some aspects of new designs for end closures.

While our Proposal and Work Plan listed our major objective as "development of at least one new system—that will be *highly effective* in containing and controlling emissions from the ends of ovens" (no standard given), our target is complete elimination of emissions—including the first hour of any coking cycle—over a long period of operational time. Whether or not this can be achieved with the recommendations included in this report remains to be established.

(2) Some of the comments and judgments in this report could be construed as being critical of existing door-sealing designs and of the approaches of the builders of coke batteries. In addition, discussion of any aspect of coke-oven design is a sensitive subject for one commercial interest or another. It should be appreciated that we are evaluating designs developed in the early 1940's (or earlier) when there was a different set of performance standards and competitive restraints. Our attention is directed towards the good and not-so-good features of standard designs as referenced to a new set of performance standards. In instances where we have judged that some feature of a design is desirable and should be retained, we have given credit to the builder.

Our discussions with builders have been limited, possibly because they are actively developing their own new and retrofittable designs. If this is the case, this bodes well for the development of several acceptable upgraded systems.

(3) Almost all of the older coke batteries in North America (all shorter than the newer 6-meter batteries) have been built by either the Koppers or Wilputte engineering organizations. The major thrust of our research effort has been to develop upgraded, retrofittable metal seals for the replacement of existing seals on these "brands" of batteries. Within each brand of battery there are variations

in size, age, and design. Our development of engineering drawings (Task 5 is now in progress) will, however, be based on "typical" end closures of these two companies. Koppers and Wilputte furnished Battelle-Columbus with end-closure drawings that they consider to be typical. For this cooperation and for these drawings we thank these two organizations. It is expected that the manufacturers of upgraded seals will be able to modify the recommended seal design to fit variations in the existing sizes and designs of end-closure elements.

(4) Because of the large amount of work that has been done and the large amount of data obtained, our Sponsors have requested that this interim report be presented concisely. Therefore, we have not included the working paper summaries of Tasks 1, 2, and 3 in this report. Where necessary to our conclusions and recommendations, we have included extracts from these working papers. Copies of these working papers have been sent to our Sponsors' representatives and copies can also be made available to those with specific interest in details and in mathematical analyses. We suggest that the EPA/AISI report entitled "Study of Concepts For Minimizing Emissions From Coke-Oven Door Seals" be considered as reference material for this report.

(5) Measurements during this study were made in terms of customary U.S. units. However, measurements of base units (length, mass, time, and temperature) are reported in SI units, in general agreement with conversion practices as given in ASTM Designation E 380-72; "Standard Metric Practice Guide; A Guide to the Use of SI". To enhance readability and rapid comprehension, customary U.S. units often are also given, and customary U.S. units are used for derived units (such as energy, force, pressure, and power).

CHAPTER II

ANALYSIS OF METAL-SEAL SYSTEMS AND RETROFITTABLE METAL-SEAL RECOMMENDATION

The conclusion of the 1975 EPA/AISI report ("Study of Concepts For Minimizing Emissions From Coke-Oven Door Seals") was that, of all the concepts considered, Battelle researchers rated *upgraded* metal-to-metal seals as the best retrofittable approach to minimizing the emission problems from coke-oven door seals. Only upgraded metal seals were given a rating indicating a 90 to 100 percent probability of successful development and successful performance within the criteria specified jointly by the EPA and the AISI. This chapter presents a summary of new work completed to advance the state of the art for upgraded, retrofittable metal-to-metal seals.

Comments on Standard Designs for Seals

Of the coke-oven batteries that have metal-to-metal seals, about 25 percent have the fixed-edge design shown in Figure II-1. About 70 percent have the S-shaped design shown in Figure II-2. Our research and development target was to evaluate the technical strengths and limitations of these designs, and either to upgrade one or both of these designs to obtain improved performance, or to recommend new designs and materials. As a basis for evaluation and subsequent conclusions and recommendations, the inputs from Tasks 1, 2, and 3 are presented in the following paragraphs.

Input From Tasks 1 and 2
(Mathematical and Physical Modeling)

All of the end-closure components play some role in sealing the ends of coke ovens. Most of these components, however, play a minor role compared with (a) the conformity of the jamb-seal surface and the seal edge, and (b) latch force. Seals and latch forces are discussed in this section of the report. Jambs and other related aspects of end closures are covered in other chapters of this report.

Fixed-edge seals and S-shaped seals were considered in this study. These will be shown in more detail in the following discussion. In addition, there is a variation of the fixed-edge seal often called the "knock-type" seal. One example of this variation is shown in Figure II-3. With the popular fixed-edge seal (Figure II-4), adjustments to the seal are made by backup screws which are rigidly attached to the body of the door. In the knock seal, coarse adjustments are made with eccentric cams spaced around the periphery of the seal, while fine adjustments are made by "knocking" the seal from behind with a hammer.

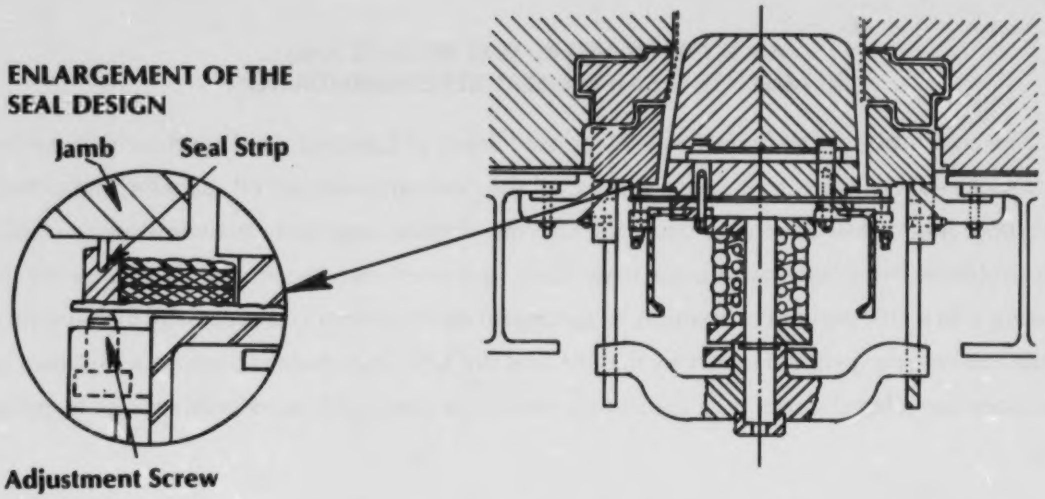
ENLARGEMENT OF THE SEAL DESIGN
Jamb
Seal Strip
Adjustment Screw

FIGURE II-1. CROSS SECTION OF A TYPICAL COKE-OVEN DOOR WITH A FIXED-EDGE SEAL

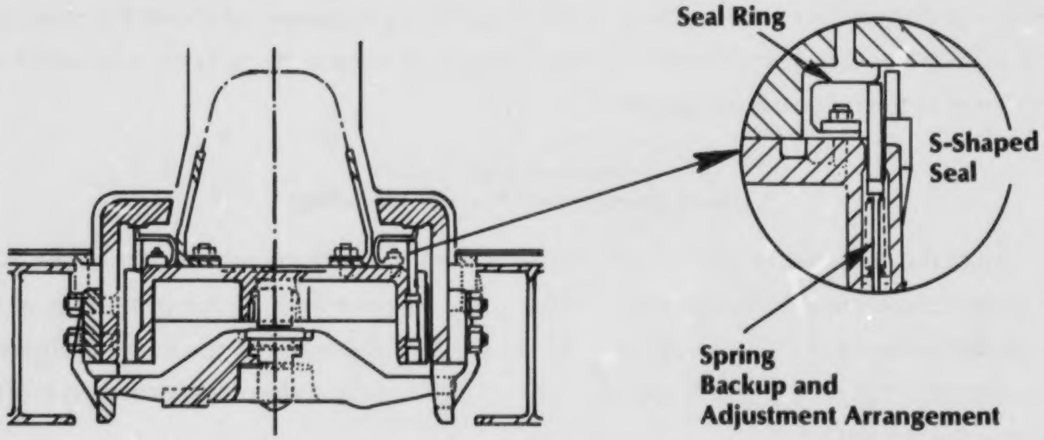
Seal Ring
S-Shaped Seal
Spring Backup and Adjustment Arrangement

FIGURE II-2. CROSS SECTION OF A TYPICAL COKE-OVEN DOOR WITH AN S-SHAPED SEAL

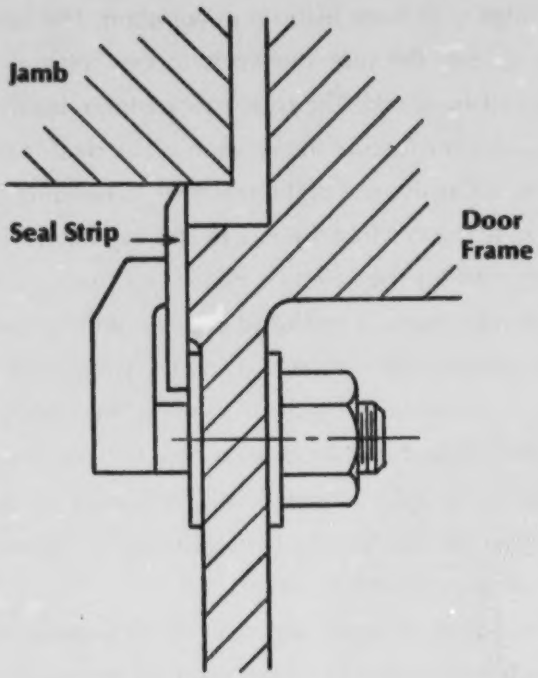
Jamb
Seal Strip
Door Frame

FIGURE II-3. CROSS SECTION OF A TYPICAL "KNOCK-TYPE" SEAL

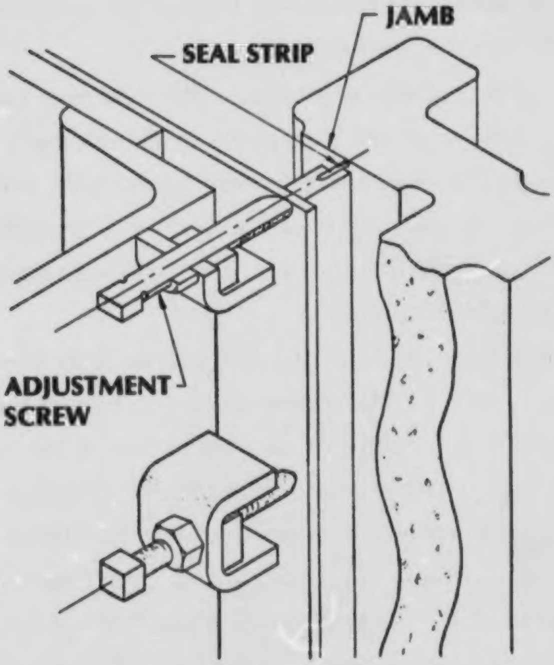
JAMB
SEAL STRIP
ADJUSTMENT SCREW

FIGURE II-4. SIDE VIEW OF ADJUSTMENT EQUIPMENT ON FIXED-EDGE SEALS

Both of the fixed-edge seals have features in common. The latch force is generated by a door-mounted spring system. Because the latch forces "clamp" the jamb and the door together, this system is self-balanced. The total contact force between the seal and the jamb equals the latch force. Another feature in common is the rigidity of the seal. Rigidity in this context does not refer to the resistance of the seal edge to bending (although this is present in these designs), but rather to the fact that these seals lack capability for automatic adjustment to small changes in the profiles of the jamb or door. This feature of the rigid sealing system manifests itself in the development of leaks and in a nonuniform sealing pressure around the seal, i.e., the contact pressure between the seal and the jamb is different at one place on the seal than another. This is depicted in Figure II-5 where the sealing pressure is shown to be significantly higher under the latches than between the latches. Once contact has been made between the seal and the jamb at the latching levels, increasing the latch pressure will increase the sealing pressure only under the latches. Thus if the seal is leaking elsewhere, only manual adjustments near the leak can cure the situation.

The two points made so far—uneven sealing pressure and low effectiveness of increase in the latch force—are easily envisioned by taking two yard sticks and squeezing them together at two locations. This is depicted in Figure II-6. The pressure between the edges of the rules will clearly be higher at the locations where the rules are being squeezed together than say between the clamps. Moreover, squeezing harder will make little or no change in the contact pressure at locations between the "latch levels".

Because of the preceding two points, and because the rigid seals cannot of themselves assume a different contour, rigid seals are susceptible to development of leaks if a slight change in the contour of the jamb or door arises because, for example, of changes in the thermal gradients. Such leaks can be stopped only by adjusting the seal manually with the available devices. Adjustments to the seal while the door is in place can have several possible consequences, each of which needs to be considered.

Recall from preceding discussions that the latch force is distributed around the seal/jamb interface as a contact pressure which we have referred to as the sealing-pressure distribution. The total latch force equals the sum of the contact force around the seal perimeter. Any manual adjustment to the seal is made with the intent of changing the seal pressure somewhere around the seal, most probably to increase it from zero where a leak is occurring. Thus, any adjustment will either increase, leave unchanged, or decrease the total latch force and will redistribute the seal pressure. Because intuition says that if there is a leak there is a gap, and, if the seal edge needs to be advanced to close the gap, most adjustments will result in

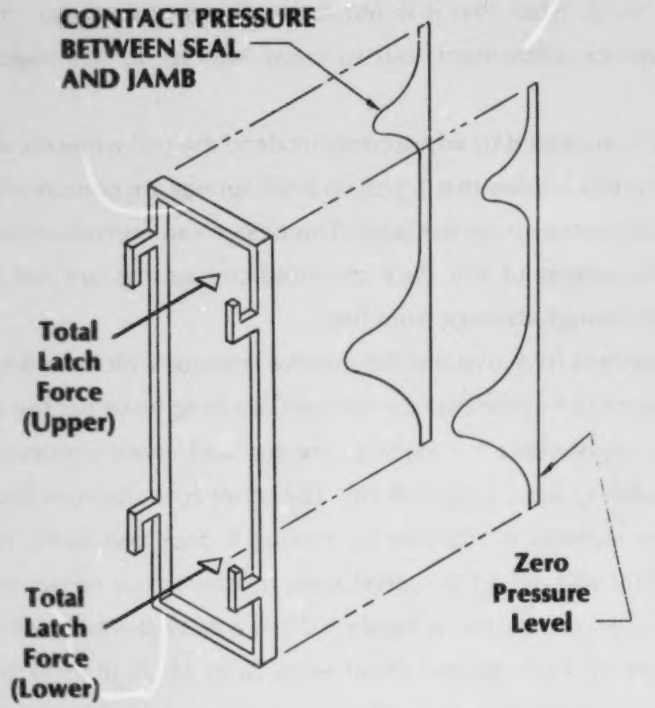
CONTACT PRESSURE
BETWEEN SEAL
AND JAMB
Total
Latch
Force
(Upper)
Total
Latch
Force
(Lower)
Zero
Pressure
Level

FIGURE II-5. DISTRIBUTION OF SEALING PRESSURE

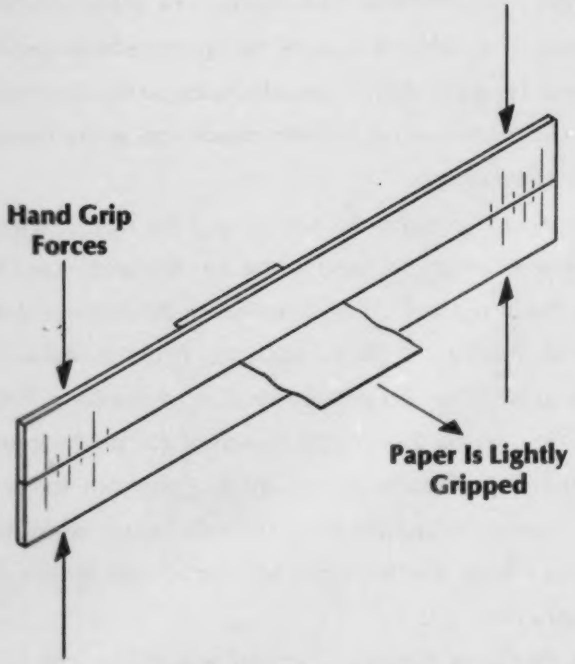
Hand Grip
Forces
Paper Is Lightly
Gripped

FIGURE II-6. AN EXAGGERATED REPRESENTATION OF THE CONTACT PRESSURE DISTRIBUTION BETWEEN TWO CLAMPED RULES

increasing the latch force. Note that it is not inconceivable that a gap could be closed by loosening the appropriate adjustments but to know how to do this requires skill and experience.

If the latch force is increased by adjustments made to the seal while the door is in place, in the fixed-edge systems this implies that the main latch springs are compressed further and the door main body is a bit further from the jamb. This design can reproduce this increased latch force on the next placement of the door provided the springs are not fully compressed through relaxation or through damage from fires.

The fixed-edge designs have two distinct positive features which need to be emphasized. One of these is the point just made that the springed latching force has the ability to increase and decrease as fine adjustments are made to the seal and, more importantly, the ability to reproduce this new sealing force automatically. The other advantageous feature is the way in which the entire seal element is adjusted by moving it back and forth. These features are recognized as important and will be discussed again relative to our recommendations.

The S-shaped seal system shown in Figure II-7 has a more flexible sealing element and is backed up by springed plungers spaced about every 20 to 25 cm (8 to 10 inches) around the seal. These devices give adjustability but with the retention of flexibility at the seal edge. The latch force in this system is usually applied by a screw mechanism that is motor driven and cuts off by means of a current limiter to the drive motor. The motor and drive are a part of the door-handling equipment. One other feature of this system which does not show in the figure is the presence of stops to keep the door from advancing so far as to overstress the seal. These stops are at the corners of the doors on 4-meter ovens and at the corners and two places in between on the taller 6-meter ovens.

The important differences between this system and the rigid seal systems are in the latch-force devices and in the seal design. Because of the way the latch force is generated on the S-shaped seal system, it will not respond to adjustments in the manner described previously for the rigid seals. Here, with the door in place, adjustments to the seal will again most probably increase the latch force above what was present on placing the door. Assuming the latch force to be increased in this way, when the door is removed for pushing and then replaced, the door-handling machine will essentially reproduce the previous lower latch force. This will cause still another distribution of latching force. If leaks occur, adjustments will increase the latch force once more to a level which cannot be reproduced by the drive motor when the door is placed in the next cycle.

This difficulty with the more flexible S-shaped seal system can be overcome by incorporating a spring-latch system along with the spring seal.

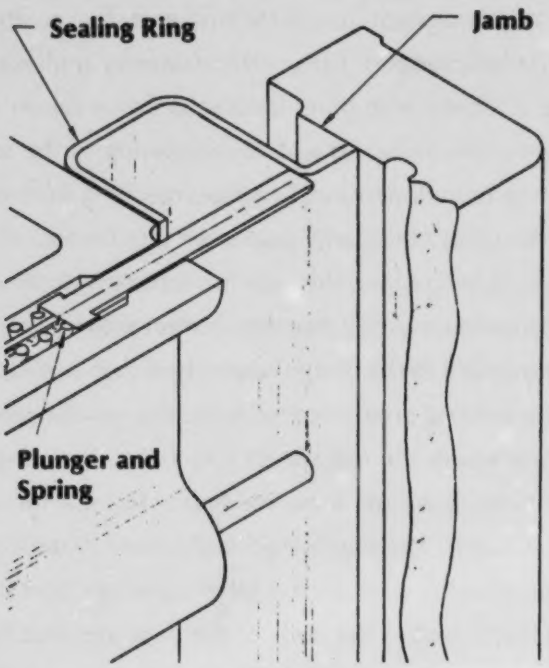

FIGURE II-7. SIDE VIEW OF S-SHAPED SEAL SYSTEM

There are advantages of the flexible seal which are worth noting. Flexibility is used in this discussion to mean the ability to flex or to bend in a spring-type fashion. Thus, the flexible seal can automatically adjust to small changes in the jamb or door profile without losing sealing pressure. Flexibility also means that the sealing pressure at any point can be about the same as at any other point—that is the sealing pressure can, in theory, be relatively uniform around the door. A final advantage which can be expected but which is not quite so obvious is that, for a given latch force, the flexible seal is capable of sealing a greater mismatch between the contours of the seal and the jamb. While this was expected, the Task I analysis indicated that the difference is more than minor.

Up until this point in our discussion, the topics have been limited to features which were particular to either the rigid or to the flexible seals. Certain features which they have in common are also worthy of mention. One way a seal edge can be permanently damaged is by subjecting it to a force which develops stresses in excess of its yield strength—a property of the material. Both flexible and rigid seals are easily damaged if they are banged against the jamb or against the latch hooks by the door-handling machinery. But there are other, and more-subtle ways of damaging a seal by overstressing. Both of the sealing-system designs have a common feature that is undesirable and which the research team has termed "point loading". Referring to the drawings of the various designs, it is clear that each seal is affected from the rear by cams, screws, or spring-loaded plungers. Each of these devices applies a force at a small area at the back of the seal. The difficulty with point loading is that it causes a stress concentration, particularly on the more flexible S-shaped seal. Overstressing of the seal at such a point can result in damage by yielding or in dimensional changes resulting from creep and relaxation. In addition, point loading does not necessarily guarantee distribution of the load between the points of force application. In this regard, the situation is somewhat similar to that described in the previous discussion concerning latch-force distribution with fixed-edge seals. It is for these reasons that it was recommended to the design researchers that consideration should be given to the elimination of point loading on the rear of seals. This recommendation was considered to be particularly important where the seal system is to have a high degree of flexibility.

A more difficult similarity to discuss is the yielding of the seal member through bending. The rigid seals are bent as a unit. The entire rigid seal is bent or deflected to attempt to conform to the jamb contour. Flexible seals on the other hand are bent in a rather complicated way. The rear of the seal is attached to the body of the door and thus has the same contour as the door. The sealing edge, on the other hand, is loaded by plungers and bends in a way that may be contrary to the rear of the seal. Thus the seal is being asked to contort in ways which may cause it to yield permanently. The analysis in the Task I effort also showed that the amount of forward or backward adjustment of the spring seal that can occur before it yields depends upon whether only the leading edge of the seal is bent to conform to the door profile or whether the entire seal is customized by initially shimming it to match the jamb profile.

The physical-modeling experiments in Task 2 were concerned mainly with a study of thermal-stress variations in jambs and doors. Rather than attempting to evaluate new seal designs on the heated quarter-scale model, the work plan calls for evaluation of full-size sections of seals in a separate task (Task 5). This work is now in progress.

During physical-model experiments, however, it was learned that even a small fire burning at a gap between a seal and jamb can heat the seal material to about 810 K (1000 F). Because of the thermal mass of the jamb and door, these components do not rise rapidly in temperature when near small fires. It was judged that localized heating by fire of any seal design/material under conditions of constraint and seal-bending stress can be detrimental to the seal.

When the physical model was cycled in temperature to mimic operational conditions, sealing between the seal and the jamb was not lost at any time. Although the temperature levels were changed, the temperature gradients remained almost constant. The gradients remained near constant because the temperature changes occurred slowly. Tests were run in which the end-closure component gradients were increased rapidly by spraying water against the equipment in a simulation of a rain storm. There was a decrease in latch loads during the water-cooling period. This decrease had to be accompanied by a change in the distribution of sealing pressure and a change in the profile of the door or jamb, or both.

Input From Task 3 (Field Data Collection)

When obtaining measurements of jamb profiles at 4-meter and 6-meter batteries having both S-shaped and fixed-edge seals, the performance of seals was observed and numerous discussions were held with operational personnel about their experiences (and improvement approaches) with the performance of the two types of seals. Information that relates to our objective of upgraded metal seals is as follows:

S-Shaped Seals

Members of the project team have witnessed 100 percent emission-control performance with *new* and well-adjusted S-shaped seals in operation against relatively straight and relatively clean *existing* jambs. Performance of "100 percent" means no visible emissions at any time, including the period during and just after charging of coal to the oven. "Well-adjusted" means that considerable skilled effort was expended to adjust the plunger-spring pressures that are acting as a point loading against the back of the seal edges. This observation relating to seal performance agrees with the analysis summary of Task 1 to the effect that the S-shaped seal is fundamentally a good approach. This observation also confirms that, in general, the metal-to-metal seal approach is sound.

However, it was observed that with time (often less than 6 months), the emission-control performance of these standard seals begins to deteriorate.* Deterioration of standard S-seal performance also occurs at 6-meter batteries where the jambs are mechanically cleaned, the jambs are not warped, and the seal edges have not been nicked. Reasons for this deterioration will be discussed in a later section.

Fixed-Edge Seals

Members of the project team have never witnessed 100 percent emission-control performance with fixed-edge seals. Operational personnel were asked in several instances to attempt to reach 100 percent control by adjusting the seals working against both well-cleaned jambs and uncleaned jambs. It is appreciated that it takes skill and experience to adjust a fixed-edge seal, because the seal itself acts as a beam so that forcing it inward at one location can result in a rocking action causing a force on the beam acting outward at another nearby location. Even with diligent and experienced effort, 100 percent emission control was never achieved. Leakage is particularly severe when attempting to adjust the fixed-edge seal in contact with a clean jamb. This is a negative observation on fixed seals, but it should be noted that there is at least one battery having fixed-edge seals that has a low percentage of leaking doors. It has been stated that, to reach a standard of less than 10 percent leaking ovens on a battery, it is necessary to lower the average leaking time per oven (both doors) below 1 hour. There is at least one fixed-edge-seal battery where the oven leaking time is rather uniformly between 15 and 20 minutes, indicating about 3 percent door-leakage rating for the battery. Our investigation at one of these "rapid-sealing batteries" indicates that (a) the jambs are only mildly bowed, and (b) the door and jambs are bowed in the same direction, i.e., the door and jamb were almost congruent. It was judged that the jamb deposits in this instance helped fill gaps. The amount of leakage and the duration of leakage was always high when we asked operators to scrape the jambs to bare metal.

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*At project review meetings, U.S. Steel Research personnel have reported that in 20 months of coke-plant operation, their new seal design has evidenced no sign of performance deterioration. Information on the U.S. Steel seal design should be obtained from them.

Task 1 results indicated that with fixed-edge seals it is not possible to obtain a transfer of the door-latching force to a well-distributed seal/jamb contact pressure. Considering that our research goal is long-life, 100 percent emission-control performance, Battelle researchers lost interest in the fixed-edge seal approach except for (a) the concept of attempting to achieve jamb and seal-edge congruency by moving the *entire* seal (as opposed to bending part of the seal in the S-shaped seal approach) and (b) the possibility that a flexible seal element could be mounted inboard of the existing sealing plate.

Jamb/Door-Frame Profile Relationships

Our "Concepts Report" stated rather positively that "the door-mounted seals often received the blame for coke-oven emissions, but the fundamental cause of the emission-releasing gaps is the pronounced degree of warpage that has occurred in differing degrees on most (if not all) of the 25,000 or more cast-iron jambs in operation". This is what we believed in 1975. In 1978 we say that the 1975 statement was somewhat of an oversimplification—there are other factors that are pertinent. It is the purpose of this section of the report to indicate our "shift" in stand and the relationship of this more complete understanding to our recommendations.

Based on our past labeling of the "warped" jambs as the culprit in emission problems, in this development project we initiated a subtask of Task 3 entitled "Development of a Practical

Profilometer" (for measuring jamb contours). This profilometer development, coupled with the measuring of jambs in various plants, consumed a considerable amount of effort allotted to Task 3.

With time and experience we concluded that:

(a) Operating jambs, as a generalization, are not so severely warped as we had expected nor so warped as indicated by some steel-company data that were included in the Concepts Report.

(b) Our early views considered jamb warpage to be any displacement outside of the plane between the bottom and the top of the jamb, i.e., any deviation from flat. This viewpoint had to be modified when it became apparent that (a) if a jamb were allowed to take its "natural" thermal-gradient-induced inward bow, such bowing would be beneficial in lowering the thermal-stress level of the jamb, and (b) some jambs had rather smooth inward bows coupled with door frames having about the same inward bows.* At the present time we are not concerned with any rather abrupt profile changes that may span only a short distance along the jamb. It may prove difficult for a seal to conform to these short-pitch variations. However, based on our measurements and observations, we do not expect to find many jambs having short-pitch problems. Quantification of what constitutes "out-of-bounds" warpage is part of Task 5, which has been started.

(c) The most important measurement, with regard to retrofittable seals, was found not to be that of the jamb profile itself but rather the measurement of the variation in the horizontal distance between the fastening point of the seal on the door frame and the seal-mating surface on the jamb. This distance is discussed in the following paragraph.

Measurements were taken (from a vertical reference plane) on the end closure of a 4-year-old, 6-meter battery to obtain the relative profiles of the jamb sides and the outboard side of the flat, steel-door frame. The thickness of the cross section of the steel door frame was constant along the length of the door and the measurements were used to calculate the variation in horizontal distance between the jamb and the line on the door where the S-shaped seal was fastened to the door. These data could be presented as profile relationships, but it is more informative to adjust the data to simulate the first contact of the seal and jamb. These adjusted data are as follows:

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*An inward bowed jamb or door has its ends moved away from the oven.

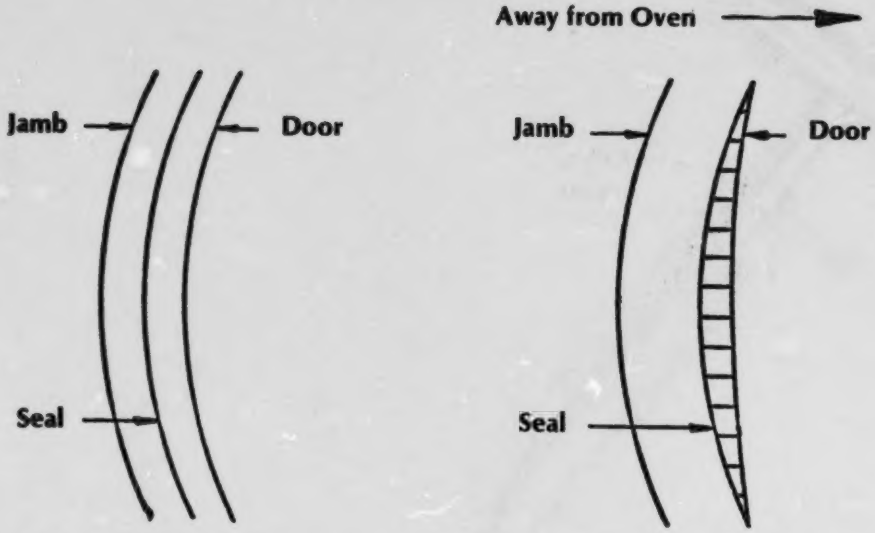
Vertical Distance from Bottom of Jamb, m		Distance Between Seal Edge and Jamb When First Contact is Made, mm	
		Left Side	Right Side
6.6		5.1	5.7
5.7	—Latch Point	2.0	2.8
4.8		0.0	0.2
3.0		0.4	0.0
1.5	—Latch Point	3.6	0.1
0.9		3.1	0.5
0.1		5.0	3.9

In this case, both the jamb and the door had an inward bow with the latched door having a greater inward bow (smaller radius of curvature) than the jamb by about 5 mm (about 0.2 inch). The measured curvature of the door was more pronounced above and below the latch points.

It was concluded that, unless the upper and lower edges of the seal had been pushed forward (inward) by increasing the backup spring pressure in these areas, upon latching the S-seal portion between the latches had to bend back about 5 mm (about 0.2 inch) before the seal edge made first contact with the top and bottom cross pieces.

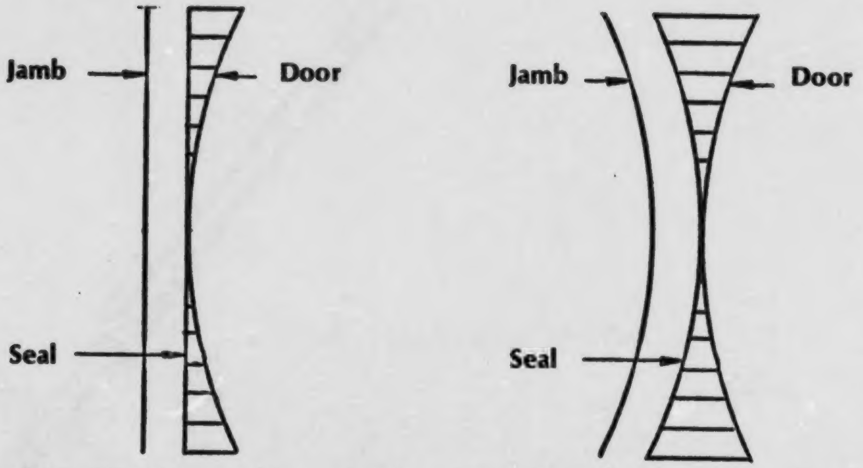
Relative to other existing jamb and door profile relationships, the above example could be labeled a "good" congruency. There are instances in which the jamb and the door body bow towards each other. A sketch of this relationship and other variations that exist in terms of relative contours are shown in Figure II-8.

Most existing coke-oven door frames are rough castings. This roughness presents a problem in terms of obtaining accurate and credible door-profile measurements. When this difficulty was encountered, the design researchers were asked to develop a tool to directly measure the distance from the jamb seal-mating surface to the inboard fastening point of the S-shaped seal on the companion door. The first tool that was designed and used is shown in Figure II-9. The way in which this tool was used is shown in Figure II-10. It is expected that this tool can be improved for use in a follow-on demonstration project. Because of the difficulty of taking readings near the top of a door, there is a pronounced tendency to take them fast, and thereby to penalize accuracy. A modification of this tool could include electronic sensing equipment, perhaps with a digital readout.


Away from Oven
Jamb
Door
Seal
Jamb
Door
Seal

Example A. Horizontal distances between jamb and door are all the same.

Example B. Door has less curvature than jamb. Jamb corners are closer to door than at the middle of jamb/door.


Jamb
Door
Seal
Jamb
Door
Seal

Example C. Door is curved inward and is facing either a straight jamb or distance between jamb and door is greater at the corners.

Example D. Jamb and door bow towards each other.

FIGURE II-8. EXAMPLES OF VARIATIONS THAT EXIST IN TERMS OF THE RELATIVE CONTOURS OF JAMBS AND DOOR FRAMES

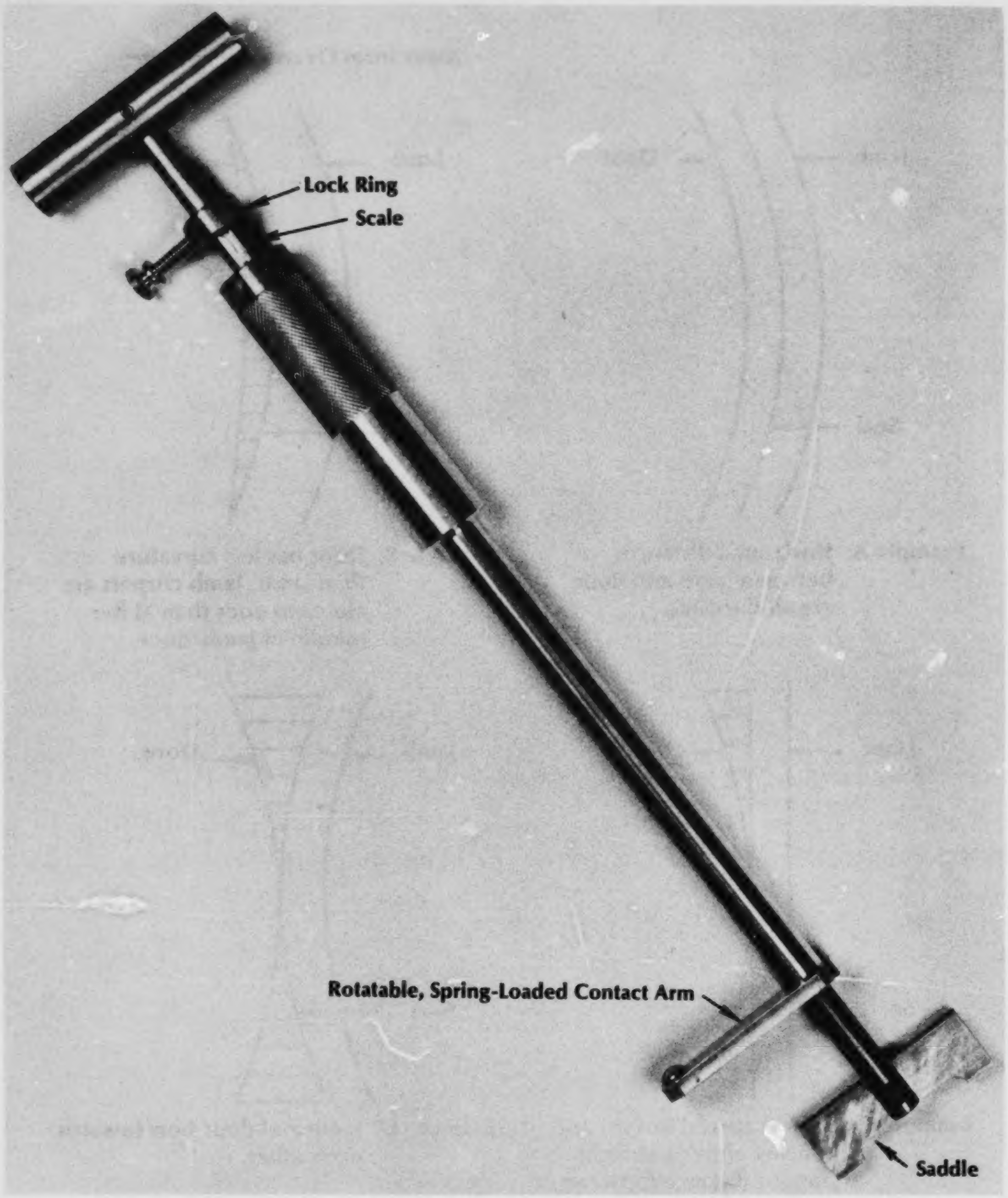

Lock Ring
Scale
Rotatable, Spring-Loaded Contact Arm
Saddle

FIGURE II-9. TOOL DESIGNED FOR MEASURING THE HORIZONTAL DISTANCE BETWEEN THE INBOARD EDGE OF ANY DOOR FRAME AND THE SEALING SURFACE OF THE ACCOMPANYING JAMB

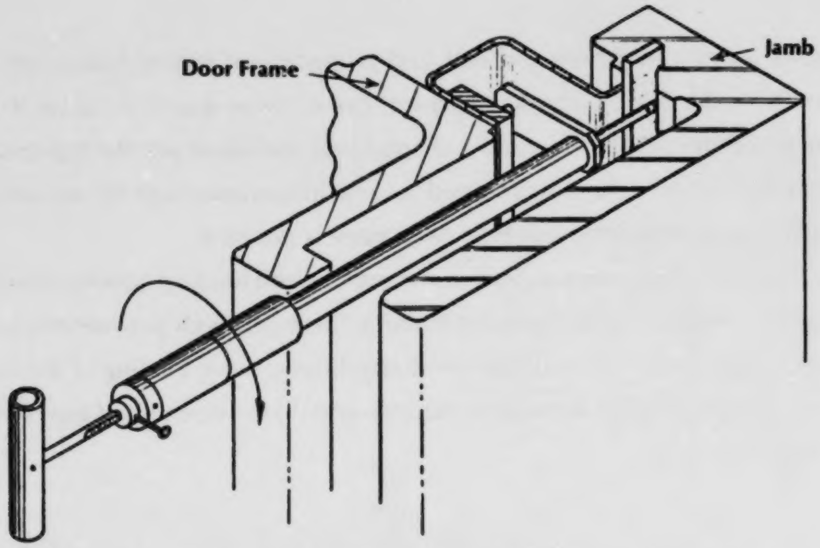


FIGURE II-10. SKETCH SHOWING OPERATION OF THE MEASURING TOOL

Distance being measured is being the seal surface on the jamb and the inboard edge of the door frame.

Damage/Changes Observed in Operating S-Shaped Seals

This section of the report deals with the observed or measured damage and dimensional changes that often take place in standard S-shaped seals.

Coke-plant superintendents often indicate that they think that their 304 stainless steel S-shaped seals are "too soft" and "damage too easily". Relative to other materials, 304 stainless steel does have these disadvantages. A comparison of 304 stainless with other materials is included in a following section of this chapter. Many examples of nicks and bends on seals can be seen on visiting or working at coke plants. It was judged that 304 stainless steel should be replaced with a harder and tougher material if for no other reason than to minimize dents and bending. With regard to this type of physical damage, Battelle researchers did not include any effort in this project to devise methods for shielding seals from bumping damage. One approach would be the retrofitting of additional bumpers and guides. There are indications that the research organizations of steel companies have done research on this subject, and that the results may become available. The development of suitable door guides and door stops is an important consideration in long-life seal performance. If required, this development may be part of a follow-on demonstration project.

Another type of visible damage is caused by the spring-plunger back-up loading of the S-shaped seal. Calculations made in Task 1 indicated that, on the average, about 70 percent of the latching load is absorbed by the spring-loaded plungers pressing against the back of the seal edge. Under conditions where the seal and plungers are forced backward in a large deflection, damage to the back of the standard seal can occur as shown in Figure II-11. Shown is a photograph of a portion of a discarded S-shaped seal. Indicated are the depressions made in the back of the seal edge by the plungers and the resulting waviness of the seal edge. According to coke-plant superintendents this type of damage is not rare.

According to calculations made in Task 1, the use of point loading (as with plungers in the S-shaped seal system) does not distribute the latching force very well between the plungers. It is also indicated in Figure II-11 that, under some conditions, point loading of the back of the seal strip can result in (a) physical damage to the seal, and (b) the opening of gaps between the seal edge and the jamb.

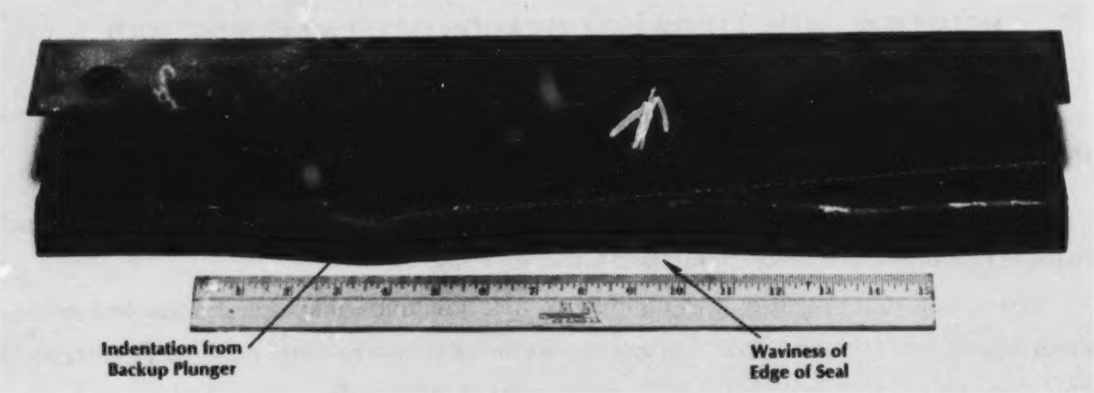


FIGURE II-11. PHOTOGRAPH OF A DISCARDED S-SHAPED SEAL SHOWING INDENTATIONS AT THE PLUNGER CONTACT POINTS AND THE RESULTING WAVINESS IN THE SEAL EDGE

Creep and Relaxation. There are indications that the S-shaped seal rather rapidly goes through dimensional changes during service. These changes occur by the action of yielding as creep and/or stress relaxation with the result that the seal edge assumes or attempts to assume the same profile as the mating jamb. U.S. Steel Research data indicate that this accommodation of the seal can take place in four coking cycles or less. This accommodation appears to be advantageous in terms of attaining congruency between seal edge and jamb profile, but gaps between the seal edge and the jamb could develop due to nonuniform plastic deformation. Battelle researchers believe that the stress level and temperature level vary along the standard S-seal. Therefore, the degree of plastic deformation could vary with the result that gaps can develop between the seal edge and the jamb.

It would be expected that the gap-forming problem caused by deformation would be more severe at coke plants where the seals are at a higher temperature than at other batteries. In general, this has been observed to be correct. It is recommended that future batteries should be designed to have significantly lower operating temperatures on all elements of the end closures. However, in terms of retrofit, one approach to be considered is the use of materials more resistant to plastic deformation.

Changes in Jamb and Door Profiles. The degree to which operating jambs and doors change their profiles during temperature gradient changes has a bearing on the amount of flexure that will be required in upgraded seals. The results of our measurements, with comments, are included in Chapter III of this report. Chapter III deals with retrofittable jambs.

For this seal chapter of the report, it is appropriate to state that our greatest concern with changes in relative profile relates to the changes that occur during rain storms that rapidly cool the door and the jamb. This problem is greater in the taller ovens because the degree of bowing is a function of the square of the height (all other factors being equal).

Seal Adjustments and "Life on the Bench". To a limited degree, both the fixed-edge seal and the S-shaped seal are adjustable. As noted in the introduction to this section of the report, if a considerable amount of "tuning" of a new S-shaped seal is performed by skilled personnel, a new S-shaped seal can be made to be 100 percent emission free—for a time, and if the door-to-jamb spacing is within the limits of the adjustability of the seal. This can be done, but it is not being done, or it is not being done often. There are probably more reasons for why it is not being done than we appreciate, but, based upon our experience, it is not being done mainly because there is really not enough time between equipment moves to do the job efficiently or effectively. Adjusting seals or making repairs (patching) on oven ends is somewhat akin to doing ceiling repairs in an operating subway. You have to know the schedule and estimate the time you have to work. With this information in hand, the next decision to make is whether to attempt to do the job working from the ground (the bench) or do it right and get up to the job. Given that the "work" is at the top of the jamb, the next step is to move the scaffolding equipment into place (team operation) and start climbing. Once in place, whether doing measurements or repairs, the feeling persists of "get the job done fast and get the heck down from there". This feeling exists because it is not unknown for a machine operator to "wipe out" a scaffold arrangement on the bench. In moving from working on a 4-meter battery to working on a 6-meter battery, the difference is somewhat akin to working on a step ladder as compared with working at the top of a long extension ladder. In summary, the equipment and the tools and the time are just not available for the job that has to be done. For the taller batteries of the future, we suggest that the designers first personally work for a brief period at the top of jambs and then perhaps equip the battery with powered monorail cabs for single-man repairs.

As a result of our own experiences taking measurements on jambs and doors, it was suggested to our designers that "to the degree possible, attempt to eliminate the need for above-the-bench adjustments". Based upon our discussions with coke-plant supervisors, this approach has to be demonstrated before industry acceptance is obtained.

Input From Other Sources

Prior to the start of this project, it was understood that steel companies having data on end-closure measurements and seal performance would share these data with Battelle researchers. One of the objectives of this sharing was to minimize the duplication of efforts. In the introduction to this report, special acknowledgment was given to the Research arm of the United States Steel Corporation for forwarding to Battelle a detailed report entitled "Coke Oven-Door System Technology; Field Data From Clairton Works".

Some of the data presented in this USS report were new to the project team and some of the data confirmed our own measurements. Some of the more important information extracted from this report is as follows:

1. Most of the measured gaps between S-shaped seals and the jambs were in the range of 0.4 to 0.8 mm (0.015 to 0.030 inch). For this size of gap, sealing time (filling with tar) exceeds 1 hour.
2. The temperatures of seals and their temperature profiles varied from cycle to cycle.
3. USS researchers recorded an unusual temperature excursion during the period when they were monitoring seal temperatures. With a door on an empty oven for about 3 hours, the maximum seal temperature reached about 660 K (725 F). At this point, the aspiration steam was turned on for charging. The seal temperature rapidly rose to 710 K (820 F), but began to fall rapidly as the oven was charged. In subsequent tests, this temperature excursion was not duplicated.
4. Periodic measurement of the vertical contour of the seal edge interfacing with the jamb (taken with the doors off the oven) indicated that the seal edge rather rapidly developed a permanent "set" in conformation with the jamb contour. These measurements were taken after four coking cycles. It was stated, however, that this yielding of the seal edge to assume the contour of the jamb did not necessarily, by itself, result in satisfactory sealing.

The above extracts are not direct quotes from the USS report. The information on the yielding of the S-shaped seals was particularly important to the project team.

General Requirements for Upgraded Metal-Seal Systems

This present development project is an outgrowth of a preceding project. As in the preceding project, the Sponsors specified that they wanted an analytical approach as contrasted to an empirical approach.

The original scope of work for the Concepts Project, as stated by the joint contract with EPA and AISI, specifies that the techniques and technical advances developed should meet, to the greatest extent possible, the following *functional* criteria:

(a) Capable of being retrofitted to current and contemplated slot-type coke ovens, encompassing all oven heights and construction types
(b) Compatible with existing door-handling and oven-end working machinery
(c) Operability and reliability commensurate with present coke-oven practice
(d) No creation of additional or different environmental problems
(e) No adverse effect on product quality.

During the Concepts Study, *evaluation* criteria were developed by joint efforts of EPA/AISI/BCL. In this instance each criterion was given a weighting factor to indicate a relative degree of importance. These evaluation criteria (with comments) and the weighting factors are as follows:

Criteria Listing	**Weighting Factor (Scale of 1 to 10)**
1. Relative Effectiveness to Lower Emissions (Stop Smoke)	(highest rating) 10
2. Low Operating and Maintenance Cost	10
(Note that the above criteria are rated higher than initial cost or development cost)	
3. Capability of Retrofit	9
4. Relative Life (Longer than the standard seals)	8
5. Avoids New Safety or Environmental Problems	8
6. Avoids Increasing Length of Door-Handling Cycle	7
7. Equipment Less Sensitive to Damage, Error, Abuse or Nonstandard Operating Conditions	6
8. Relative Cost Installed	6
9. Avoids Affecting Coke Quality	6
10. Availability of Expendable Materials or Components	4

11. Does It Decrease Operation Complexity and/or Minimize Operator Options?	4
12. Relative Maintainability	4
13 Cleanability	2
14. Operator Skill Requirements	2
15. Cost for Development	1

In addition to these jointly developed evaluation criteria, in the Concepts Report Battelle researchers added additional *technical* specifications in question form as follows:

1. Will it tolerate a 480 to 590 K (400 to 600 F) operating temperature?
2. Will it tolerate a temperature excursion to 700 K (800 F) for short periods without destruction?
3. Will it have increased gap-closure capability?
4. Automatic gap-closure capability? (Can the need for manual adjustments be avoided?)
5. Resistant to corrosion and chemical attack?
6. Total-failure proof?
7. Avoids new cleaning problems?

After the presentation of our recommended seal design/material, the new seal will be critiqued using the above criteria as a frame of reference.

Technical Conclusions and Recommendations
(Input to the Design Task)

The summaries of Tasks 1, 2, and 3 with reference to seals have been presented in non-mathematical terms in foregoing sections of this Task 4 report. These first three tasks provided the source material for the list of conclusions and recommendations that were developed in the early part of Task 4 (Analysis, Evaluations, and Recommendations). These conclusions and recommendations lead to the preliminary designs presented later in this chapter. The conclusions and recommendations were:

1. FOR MAXIMUM VISIBLE EMISSION-CONTROL EFFECTIVENESS, CONVERT ALL FIXED-EDGE AND S-SHAPED SEALS TO UPGRADED SPRING-TYPE SEALS. SPRING-TYPE SEALS HAVE INHERENT ADVANTAGES IN TERMS OF (A) IMPROVED CONTROL OF EMISSIONS DURING THE EARLY PART OF THE COKING CYCLE, (B) ACCOMMODATING SMALL CHANGES IN DOOR AND JAMB PROFILES EITHER DURING IN-CYCLE VARIATIONS, OR TEMPERATURE EXCURSIONS CAUSING HIGH THERMAL GRADIENTS IN THE END-CLOSURE COMPONENTS.

Most fixed-edge-seal end closures need the retrofit of a spring or flexible type of seal to meet performance standards. There may be some batteries with fixed-edge seals that, as they stand, (or with an increased level of manual adjustments) will meet some accepted standard of performance. Where standards are being met, retrofit to spring-type seals will depend upon a costs/benefit evaluation.

2. THE NEW SPRING-TYPE SEALS SHOULD HAVE NO POINT LOADING OF ANY KIND. THIS MEANS A SHIFT AWAY FROM SPRING-LOADED CONTACT POINTS TO HAVING THE SEAL DESIGN/MATERIAL ABSORB ALL OR ALMOST ALL OF THE LATCHING FORCE.

   Stop-bolts may be used to limit the maximum deflection of the seal, depending on the particular combination of seal and material recommended.

3. DEVELOP A PREFERRED SEAL-ADJUSTMENT METHOD THAT MOVES THE ENTIRE SEAL ELEMENT IN OR OUT RATHER THAN BENDING ONE PART OF THE SEAL TO MAKE A CLOSURE. TO BE CONSIDERED ARE THE RELATIVE MERITS AND COST OF MECHANICAL ADJUSTMENTS VERSUS PERIODIC SHIMMING OR SPACING ADJUSTMENTS.

   This will (a) help to distribute the latching force more evenly in terms of seal/jamb contact pressure and will also (b) tend to average out the stress level at various locations on a seal by minimizing the high-pressure points and "filling" in the low-pressure (or no contact) points.

4. CONSIDER THE USE OF HIGH-PERFORMANCE, HIGH-TEMPERATURE ALLOYS FOR SEAL CONSTRUCTION. THIS SELECTION IS TO BE AIMED AT:
   A. ALLOWING AN INCREASED AMOUNT OF SEAL DEFLECTION WHILE REMAINING WELL WITHIN THE MATERIAL'S ELASTIC LIMIT AND AVOIDING CREEP AND RELAXATION PROBLEMS
   B. UPGRADING THE SEAL MATERIAL IN TERMS OF INCREASING THE RESISTANCE TO DAMAGE AND ABUSE AND RESISTANCE TO THERMAL STRESS.

   It is expected that most high-temperature alloys will have acceptable resistance to coke-oven corrosion conditions.

5. THE CONCEPT OF RETROFITTING A FLEXIBLE SEAL ELEMENT IN FRONT OF THE DIAPHRAGM OF THE FIXED-EDGE SEAL SHOULD BE COMPARED WITH THE POSSIBILITIES OF INSTALLING ONE DESIGN AND SIZE OF FLEXIBLE SEAL FOR BOTH THE EXISTING FIXED-EDGE SEAL AND THE S-SHAPED SEAL.

6. SPECIAL CONSIDERATION AND DESIGN ATTENTION SHOULD BE GIVEN TO THE STRESS DISTRIBUTION THAT DEVELOPS ON FLEXING THE CORNERS OF SEAL DESIGNS.
7. CONSIDER INCREASING THE SEAL/JAMB CONTACT PRESSURE BY NARROWING THE CONTACTING WIDTH OF THE SEAL EDGE. THE CONCEPT OF HAVING A REPLACEABLE SEAL EDGE SHOULD BE CONSIDERED FOR RETROFITTING SEALS TO BE PLACED IN OPERATION AGAINST HOURGLASSED JAMBS.
8. COSTS AND IMPLEMENTATION SPEED SHOULD BE CONSIDERED IN SELECTING A RETROFIT DESIGN. IT IS CONSIDERED PROBABLE THAT THE LEAST-COST APPROACH WILL BE TO FIT A NEW SEAL INTO THE SPACE THAT IS PRESENTLY AVAILABLE.

The Recommended Design of Retrofittable Seals

During the first three tasks of this project, various design concepts and the listing of recommendations were developed concurrently. Following the final listing of desired specifications in the early stages of Task 4, various concepts were discarded until only one remained. This remaining design which became our recommendation is presented in this section. A discussion of material selection is included in a following section along with some discussion of the designs that were discarded. It should be appreciated that the recommended design/material is the result of an analytical and pre-engineering effort—the specifics have yet to be decided upon and laboratory tested in Task 5. Upon hearing an oral presentation of our recommendations, the Sponsors gave permission for the project team to proceed with Task 5. This design and laboratory testing effort is in progress.

Description of the Recommended Seal

The retrofittable seal recommended by Battelle is illustrated in Figure II-12 as it would appear as a replacement for an S-shaped seal. The seal ring is somewhat similar to that of the S-shaped seal, but is different in several features. The seal lip is 9.5 mm ($\frac{3}{8}$-inch) high instead of the approximately 25 mm (1-inch) lip on the S-shaped seal. Two bends are required to form the new seal rather than the three required for the S-shaped seal. The seal ring may be backed up by optional leaf springs as determined by the engineering effort in Task 5.

The seal ring and flat leaf springs are secured to a mounting angle which is a standard structural shape. The mounting angle, in turn, is mounted on the door frame using studs at the same locations used for mounting the conventional S-shaped seal. A spacer (whose function will be described later) is placed between the mounting angle and the door frame.

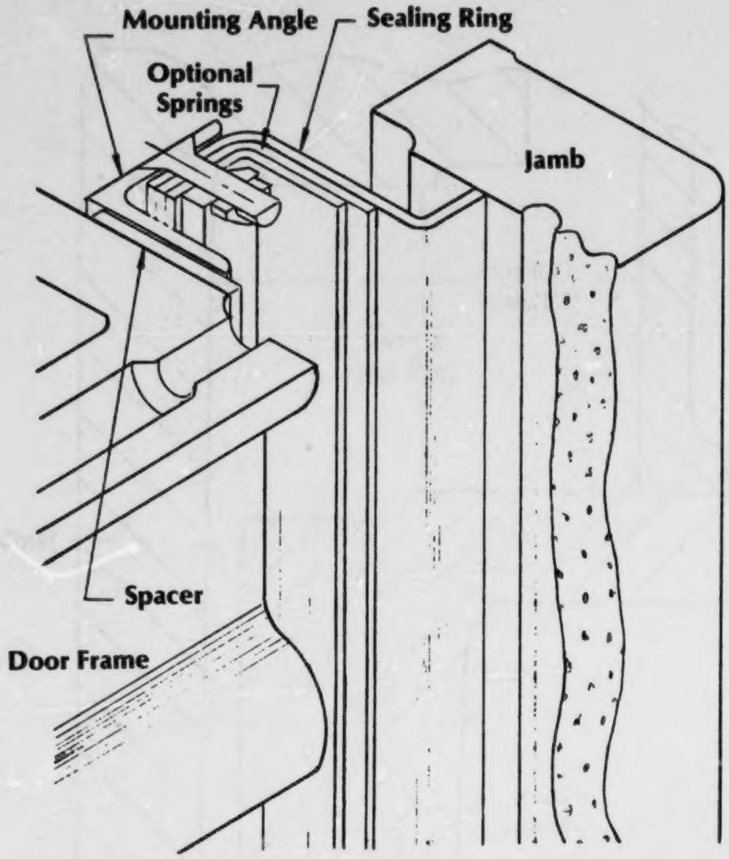


FIGURE II-12. RECOMMENDED RETROFITTABLE SEAL

Conventional gaskets and sealers are used between metal parts in the same manner as for present door assemblies.

No changes are made to the jamb, the door frame, or the lining, or to their spatial relationships.

This same seal with optional leaf springs may also be used as a replacement for a typical fixed-edge seal. However, the mounting method will be different and some modification of liner and liner retainers will be required.

The space available for retrofitting seals in a typical 4-meter Koppers and Wilputte battery is shown in Figures II-13 and II-14. These dimensions are based on reference drawings considered by the designers to be typical of each of the conventional systems in the 4-meter size range. Existing batteries may have dimensions different from the typical designs, because operators request changes at the time of construction or make modifications in later years.

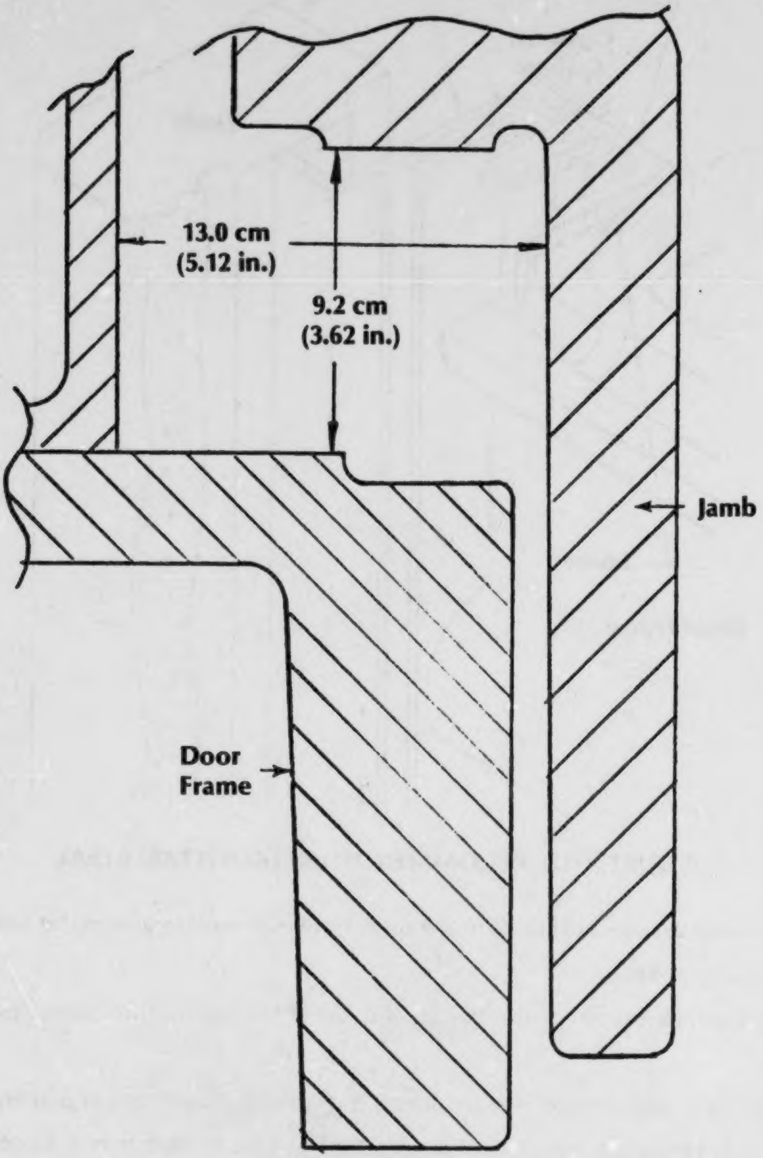

13.0 cm
(5.12 in.)
9.2 cm
(3.62 in.)
Jamb
Door
Frame

FIGURE II-13. TYPICAL KOPPERS SEAL AREA WITH SEAL REMOVED

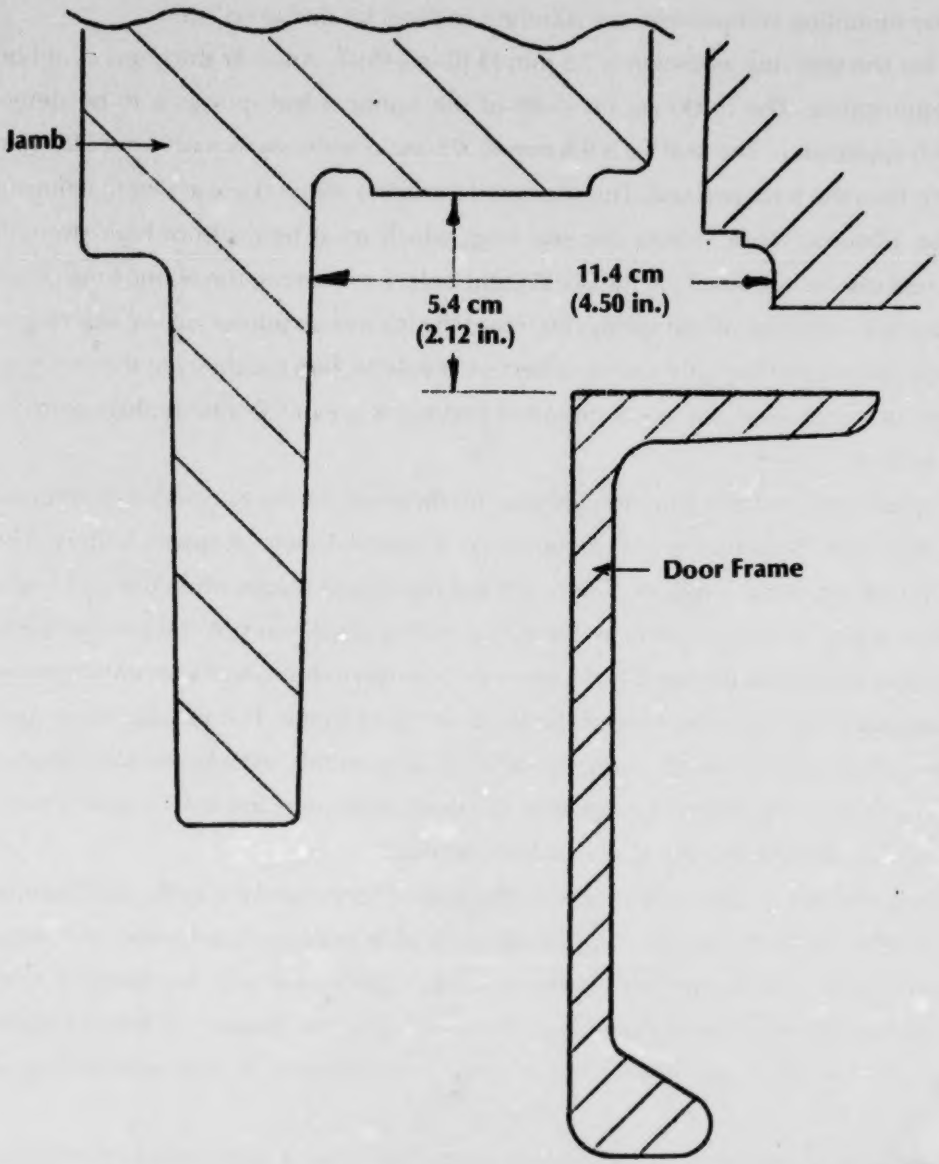

Jamb
11.4 cm
(4.50 in.)
5.4 cm
(2.12 in.)
Door Frame

FIGURE II-14. TYPICAL WILPUTTE SEAL AREA WITH SEAL REMOVED

Figures II-15 and II-16 are sections of the recommended seal as applied to typical 4-meter Koppers and Wilputte end closures. The seal ring and optional leaf springs *are the same in both cases.* The mounting components are different and will be discussed later.

Material for the seal ring as shown is 2.5 mm (0.10-in.) thick. Another thickness could be selected, as appropriate. The thickness or width of the optional leaf springs is to be determined for each application. The seal lip is 9.5 mm (0.375-inch) wide and is much more flexible along the jamb than the S-shaped seal. This increased flexibility allows the seal ring to conform more easily to a bowed jamb. Across the seal ring, which must be made of high-strength material, the seal can be deflected 7.6 mm (0.30 inch) before exceeding the elastic limit of the suggested materials. Addition of leaf springs increases the transverse stiffness of the seal ring to absorb latching forces, and has only a minor effect on the deflection capability of the seal ring.

As shown and described, the recommended seal has a greater flexibility than conventional S-shaped seals.

Mounting features for the recommended seal are different for the Koppers and Wilputte applications. Figure II-15 shows the seal mounted on a typical 4-meter Koppers battery. The seal is secured to a structural angle as shown. A fixed dimension results when the seal ring is secured to the angle. This dimension is identified in the illustration. Another dimension (between the door frame and the jamb surface) varies from top to bottom of the jamb depending on the warpage and relative bowing of the jamb and door frame. This variable dimension must be measured at selected points along the jamb by using a tool similar to one described in the summary of Task 3. The difference between the fixed dimension and the variable dimension determines the thickness of the spacer at that location.

Spacers bow the seal ring in such a manner that the seal edge (and the entire seal) assume the same profile as the jamb surface. More uniform sealing pressure is achieved with more uniform deflection all around the seal. If this minimum deflection is in the range of one-quarter to one-half the total deflection capability of the seal, the balance of the deflection ability is available for jamb and door changes during a coking cycle or over some period of time.

Several methods of installing spacers may be used. One is to use metal blocks of required thicknesses at suitable spacings. A suitable nonshrinking cement would be used to fill the gaps between blocks. Another method would use metal bars of appropriate length and thickness stacked to attain the desired space between seal mounting angle and door frame. This method, also, would require a suitable cement, but the gaps would be smaller than in the previous method.

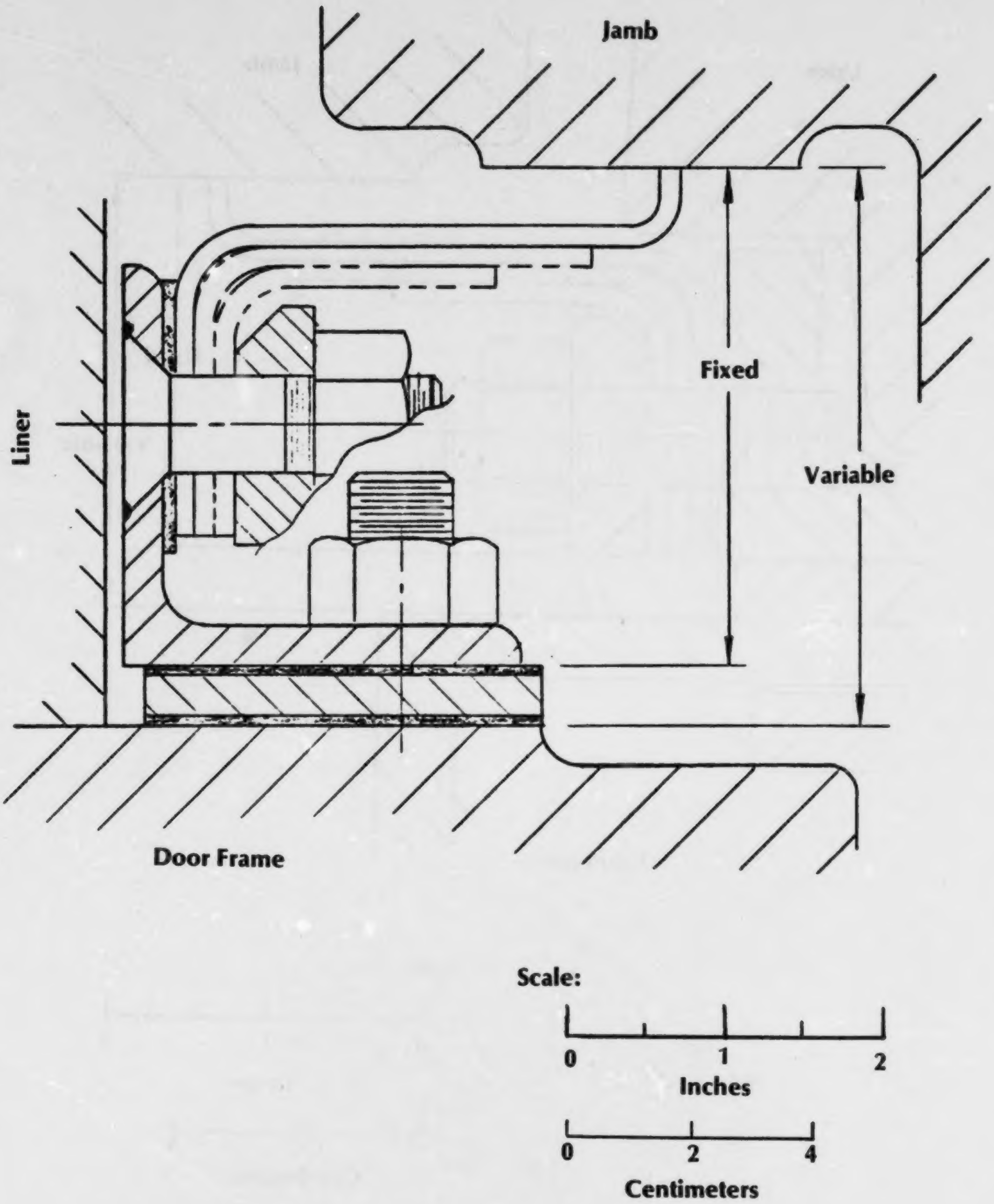

Jamb
Fixed
Variable
Liner
Door Frame
Scale:
0
1
2
Inches
0
2
4
Centimeters

FIGURE II-15. SECTION OF RECOMMENDED SEAL; TYPICAL 4-METER KOPPERS OVEN

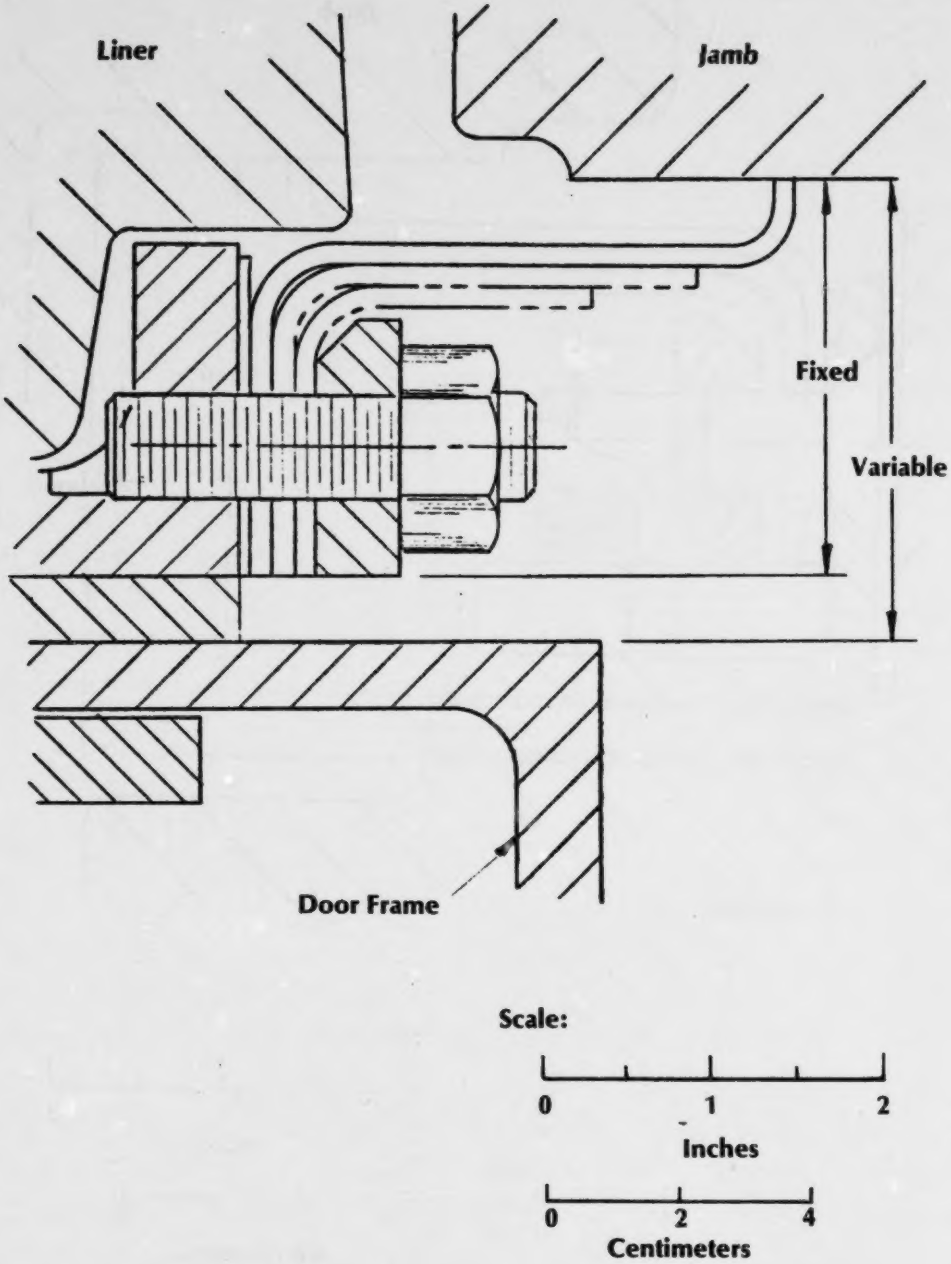

Liner
Jamb
Fixed
Variable
Door Frame
Scale:
0
1
2
Inches
0
2
4
Centimeters

FIGURE II-16. SECTION OF RECOMMENDED SEAL; TYPICAL 4-METER WILPUTTE OVEN

The use of spacers requires the following steps:

- Determine the spacer requirements from measurements taken with the door in place on the jamb. These measurements can be obtained rapidly and accurately with simple but specialized measuring equipment.
- Take door to repair facility.
- Repair door as required.
- Install recommended seal using spacers and cement as required.
- Set corner stops to avoid overstressing the seal corners while the door is being heated during the first several cycles.*
- Place door in service.

Another means for adjusting the seal ring to conform to the jamb uses mechanical screw-type adjustments. Figure II-17 illustrates a possible means of retrofitting a mechanical adjustment to typical Koppers doors. This concept, which has yet to be engineered, requires no modification of the existing door frame. Other means can be visualized, but would require expensive modification of existing door frames or design of new frames. In any event, a large number of small parts would be required.

Use of a mechanical adjustment system has features such as these:

- Mechanical screw adjustments made with the door in place eliminate the need for measurements to determine spacer thickness.
- Subsequent small adjustments are possible.
- *Skill and judgment* are required to make seal adjustments by this method.
- Misadjustments may be made by uninformed and unauthorized personnel.
- Sealing behind the mounting angle could be a problem.

Adjustment of the seal ring to conform to the jamb may be accomplished by either of the two methods described, i.e., spacers or screws. Considering the increased degree of flexibility to be expected from the recommended seal, it is believed that one setting of spacers may give an extended period of emission-free service (to be proven in a demonstration project). Our negative attitude toward mechanical adjustment screws is based on (a) the added cost and time required to retrofit adjustment screws, (b) the concern that screws will be overtightened with the result that the seals will be permanently distorted, and (c) the conclusion of the analysis work that tightening the screws with the door in place sets up an increased latching force (where screw latches are used). This latch force cannot be duplicated the next time the door is mounted on the jamb if the latch force is generated by a screw mechanism.

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*U.S. Steel Research data indicate that it takes two or more coking cycles before a door achieves its equilibrium thermal bow.

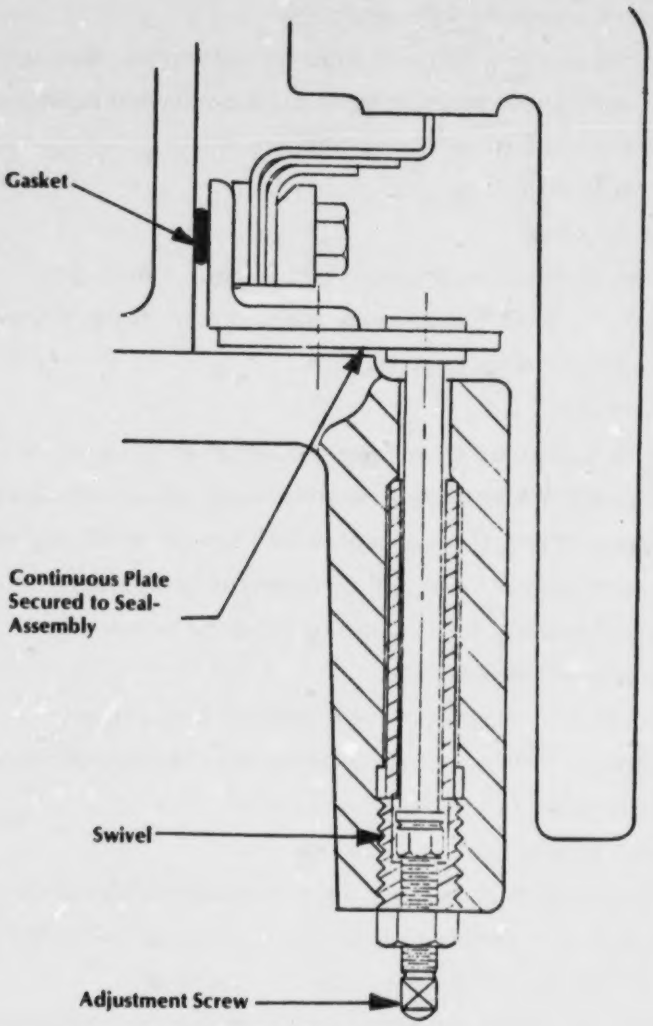

Gasket
Continuous Plate Secured to Seal-Assembly
Swivel
Adjustment Screw

FIGURE II-17. CONCEPT OF RETROFITTABLE MECHANICAL ADJUSTMENT FOR SEAL

Comments on Discarded Approaches

One of the conclusions of Task 4 was that the concept of retrofitting a flexible seal in front of the diaphragm of the fixed-edge seal should be considered. This concept is illustrated in Figure II-18. As previously noted, there is only a small space for mounting a seal as a replacement for the fixed-edge design. Therefore, the spring element must be smaller than the replacement spring element for the S-shaped seal cavity. Calculations indicate that it is not

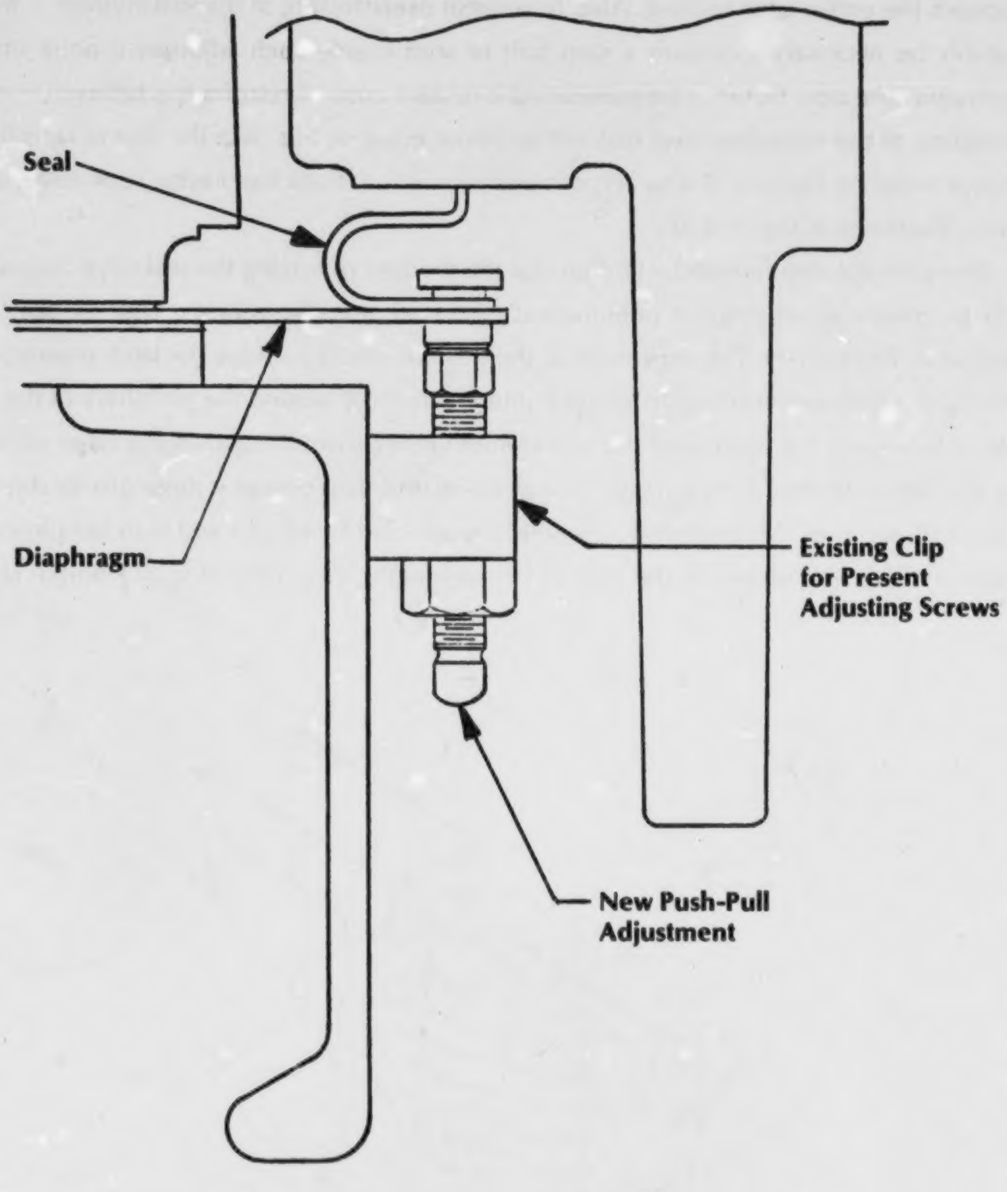

Seal
Diaphragm
Existing Clip for Present Adjusting Screws
New Push-Pull Adjustment

FIGURE II-18. ALTERNATE CONCEPT FOR WILPUTTE DOOR

possible with the smaller spring element to combine a high degree of flexibility with the ability to absorb the entire latch loading. Also, to prevent overstressing of the seal element it would probably be necessary to mount a stop bolt or stud beside each adjustment point on the diaphragm. The next factor to be considered is relative costs of retrofit. It is believed that the retrofitting of the recommended seal will be about equal or less than the cost of retrofitting concept shown in Figure II-8. Our recommendation is to retrofit fixed-edge seals with the approach illustrated in Figure II-16.

One concept that received attention was the thought of forcing the seal edge against the jamb by means of an array of pneumatically inflated, metallic bellows. This concept is illustrated in Figure II-19. The expansion of the bellows would increase the latch pressure and would also rather uniformly distribute the pneumatic force around the periphery of the seal. At least in theory, the portion of the seal element other than the upstanding edge could be thin and highly flexible. A major factor that works against this concept is the probable short life of the bellows units. Metal bellows are seriously affected by fatigue and high temperatures. Fatigue life is closely related to the ratio of stroke/length. A low ratio of stroke/length ratio is

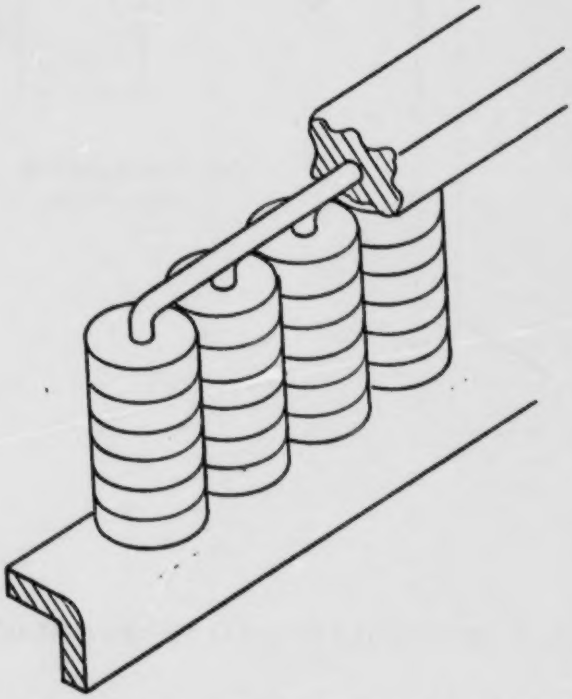


FIGURE II-19. CONCEPT USING METAL BELLOWS

desirable to obtain a long life. In this instance, a stroke of 8 mm (0.30 inch) or longer would be required. With this requirement, a long and, therefore, more expensive bellows would be required to provide a long service life.

Rationale for the Shape of the Recommended Seal (The Corner Problem)

One of the conclusions developed during this project was that special attention should be given to the stresses that develop when flexing the seals at the four corners of any door. The level of stresses at the corners relates to the shape of the seal. Figures II-20 and II-21 show two designs that are used as examples to illustrate that the orientation of the seal relative to the jamb face is an extremely important consideration in the selection of the seal design. Figure II-20 shows a sloping seal, and Figure II-21 shows a seal in which the major portion of the seal is parallel to the oven face.

Figure II-22 illustrates the action of several seals at the corner as the door is latched in place. On this figure, View (a) is the upper right hand corner of a typical standard seal in place on an oven. The deflected edge of the sloping View (b) and parallel seal shapes View (c) are also shown to illustrate the dimensional changes the seals must make as they are deflected. In View (b), a given deflection requires a relatively large change in the radius, in this case an increase. Such a change requires a corresponding change in the length of the seal edge around the corner. The seal material resists this change, and thereby stiffens the seal at the corner to the point of immobility or triggers self-destruction.

If the seal is parallel to the oven face as in View (c), the same deflection as in View (b) results in little change in radius, in this case a practically negligible reduction. Appreciable change in the length of the seal edge around the corner does not occur, and hence seal flexibility does not change at the corner.

The action of the standard S-shaped seal is illustrated in View (d). Along the sides of the seal ring, deflection is distributed over the portions parallel and perpendicular, respectively, to the jamb face; and also at the two bends adjacent to the vertical portion. At a corner, the top (or bottom) of the seal ring is joined to a side of the ring. The vertical portions of the seal are welded together to form a box-like corner thus stiffening each vertical portion and preventing deflection. The horizontal portion of the S-shaped seal is the only portion that can deflect at the corner. The result is a stiff seal with less deflection capability than along the side.

The geometric considerations discussed above resulted in the selection of the parallel seal approach.

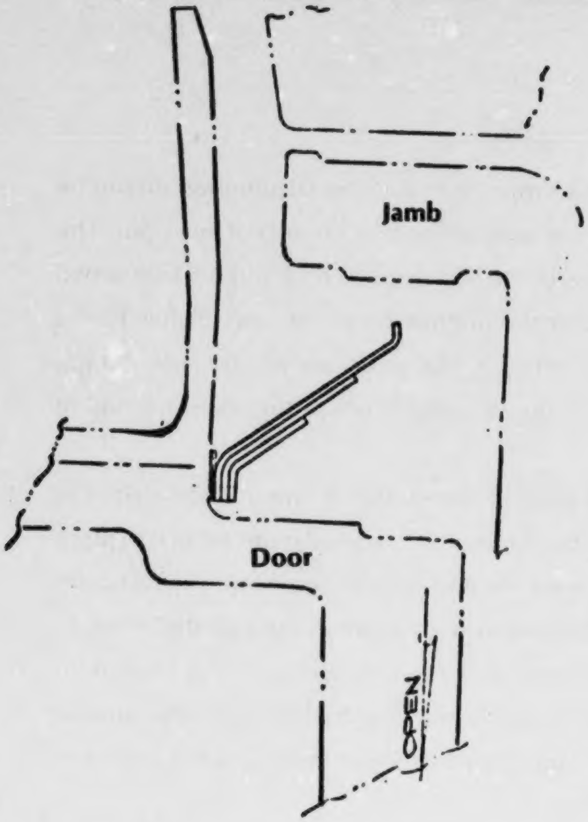

Jamb
Door
OPEN

FIGURE II-20. AN EXAMPLE OF A SLOPING SEAL DESIGN

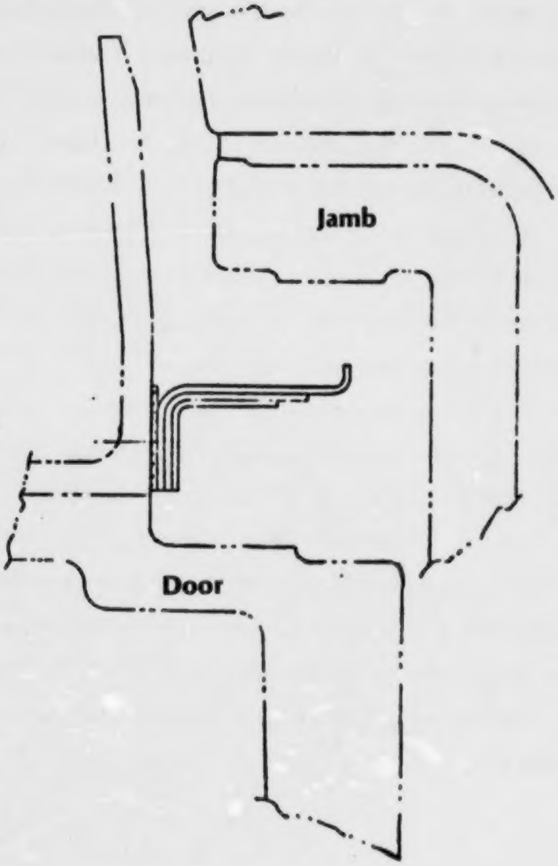
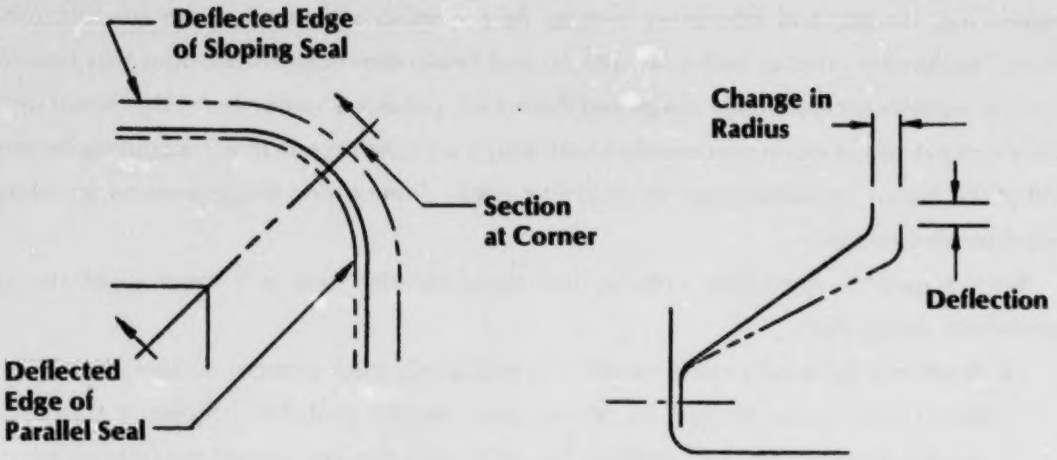
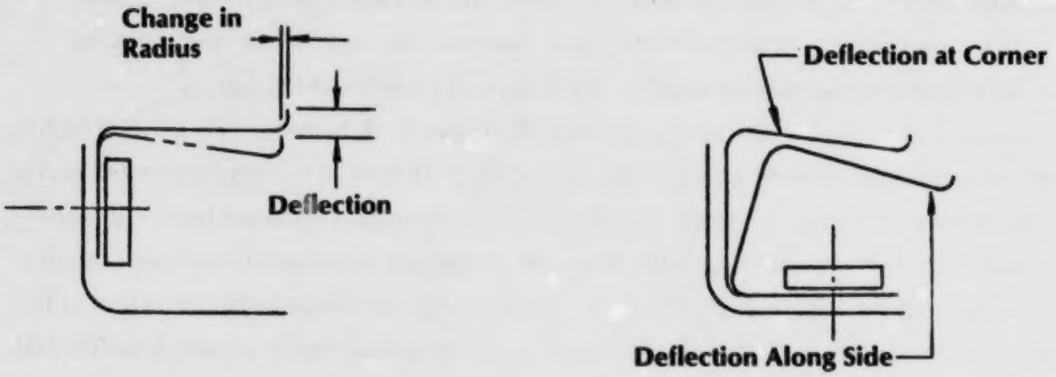


FIGURE II-21. AN EXAMPLE OF A PARALLEL SEAL DESIGN


Deflected Edge
of Sloping Seal
Section
at Corner
Deflected
Edge of
Parallel Seal
Change in
Radius
Deflection

(a) Corner of Typical Seal (Looking Toward Oven)

(b) Section of Sloping Seal at Corner


Change in
Radius
Deflection
Deflection at Corner
Deflection Along Side

(c) Section of Parallel Seal at Corner

(d) Action of S-Shaped Seal at Corner and Along Side

FIGURE II-22. SKETCHES SHOWING SEAL ACTIONS AT CORNER OF DOORS

Critique/Limitations of the Recommended Seal

The purpose of issuing this summary of Task 4 before the completion of the project was to obtain the critique of our Sponsors (and others) prior to committing a large level of effort into engineering, design, and laboratory testing. As previously described, there are functional criteria, evaluation criteria, technical criteria, and finally the recommendations that resulted from the mathematical analyses completed during this project. This portion of this report deals with a comparison of our recommended seal design with the criteria listed beginning on page II-19 of this report. In addition we are including some comments on possible limitations of our recommended design.

With regard to *functional* criteria, the recommended seal will meet all of the requirements except that:

(a) It will not be readily retrofittable to the relatively small number of doors having knock-type seals. Retrofit in these cases would probably require a major modification of the door frames. The principles that are needed for steel companies to engineer these modifications are included in this report and in the forthcoming Task 5 report.

(b) The design may or may not be applicable to ovens taller than 6 meters. One of our reservations deals with the fact that we do not know the latching arrangements that will be used for the super-tall batteries of the future.

It is expected that all of the *evaluation* criteria (pages II-19, II-20) will be satisfied by the recommended design. Sealing effectiveness is expected. The life of the recommended seal is expected to be appreciably extended over that of present standard S-shaped seals. Our definition of seal "life" is the length of time the seal gives acceptable emission-control performance. It is expected that the installed cost for the recommended seal will be higher than that of the existing seals. However, this cost criterion was given a weighting factor of only 6 by the AISI Task Force in terms of the relative importance. Estimation of the fabrication cost of the recommended seal is presently being done, but we are suggesting that the seal be evaluated on the basis of *overall* cost effectiveness. Overall cost effectiveness is defined as:

$$\frac{\text{(Original Installed Cost + Maintenance Cost)}}{\text{Effective Life}} .$$

The measure of effective life will, of course, depend upon the emission standards that are used. Field experience is required before any evaluation can be made of maintenance cost.

Battelle researchers do have some reservations about the level of emission control that will be achieved with the recommended seals at batteries that do not have mechanical jamb-cleaning equipment. There are technical variables involved including temperature,

temperature variations, type of tar, smoothness of the jamb surface, and other considerations. These variables have not been studied (particularly "type" of tar) and there are unknowns. Our concern is in sealing against hard carbon deposits on jambs that have been *nicked* in manual cleaning operations. The formation of hard carbon on jambs is far from uniform from plant to plant. Some plants, for example, have little or no carbon formation on jambs.

We believe that the technical criteria developed in the Concept Project (page II-20) will be fulfilled with the recommended design, inasmuch as it is expected to remain elastic at temperatures to 700 K (800 F) and does have increased deflection capability. During the Concepts Project, we were thinking in terms of a seal that when mounted on the door would have a wider range of flexibility in terms of "gap-closure capability", i.e., seal-edge bending. In this approach, the seal/jamb contact pressure would be low where the seal was just touching but the seal was not deflected. On the other hand, the seal/ jamb pressure would be very high where the seal was deflected a large amount. This approach was abandoned during this project with the objectives of (a) obtaining more uniform seal/ jamb contact pressure while maintaining increased deflection capability, and (b) decreasing the stress levels in the seal.

It is judged that all of the criteria/specifications developed during this project will be met. We do not foresee any new cleaning problems associated with the recommended design. However, a demonstration project is required to prove or disprove these judgments.

Material Considerations for Upgraded Metal Seals

During the course of this project, it became apparent that with the seal criteria being developed there would be a need for higher-performance materials. This section of the report deals with the criteria developed to aid in material selection. Also included are other factors that led to our recommendation that Inconel X-750 be tested in Task 5. It is expected that the evaluation of materials for seals will continue in more detail in Task 5. Our interest in this regard is related to the possible use of materials that have a lower price per pound than X-750. Because our search for materials for recommendation is not complete, this summary is preliminary in nature.

Comments on Present Seal Materials

Type 304 stainless steel is used presently for both the fixed-edge and S-shaped seals. This material has excellent resistance to the corrosive vapors that are emitted by some coals, and it has good formability. Where 304 is used to fabricate a complex shape (such as the S-shaped seal), the starting material is usually annealed strip or sheet. In this annealed condition the yield strength is only about 210 MPa (30,000 psi), which decreases to about 140 MPa (20,000 psi) at 700 K (800 F). Because 304 stainless steel cannot be heat treated to increase hardness and strength, the hardness of 304 stainless S-shaped seals is only about 160 to 200 Brinell.

The coefficient of thermal expansion of 304 stainless steel to 700 K (800 F) is a very high 17.8×10^{-6} m/m/K (9.9×10^{-6} in./in./F). This expansion rate is about 50 percent higher than that of the gray cast iron door frames to which the material is bolted. This difference in expansion coefficients presents a thermal stress situation when the seal and the door frame are heated in service. The problem becomes amplified when the seal reaches a higher temperature than the door frame.

The reported maximum allowable temperature for 304 stainless steel when used as a spring material is in the range of 530 to 560 K (500 to 550 F).* Above this temperature range, under loaded (stressed) conditions, the creep/relaxation rate of this stainless is high, and the original spring shape and/or its ability to carry the load (resist the stress) are lost. They are lost either slowly or rapidly, depending on conditions.

At some plants, carbon steel and ASTM A588 low-alloy steel are used as materials for S-shaped seals. ASTM A588 is also known as Ni-Cu-Ti because the steel contains small amounts of nickel, copper, and titanium. Ni-Cu-Ti has a yield strength of 350 MPa (50,000 psi) at room temperature. It is sold in the form of lightweight channel which is an excellent starting form for the fabrication of S-shaped seals. At some plants, this material is rapidly corroded in service. We have no information on Ni-Cu-Ti's high-temperature 533+ K (over 500 F) strength or on its creep and relaxation characteristics, but it is expected that this alloy does not have the deformation-resisting strengths required for the recommended seal design.

Material Selection Criteria

Over the time period for Tasks 1, 2, and 3; a list of criteria evolved for the selection/evaluation of materials for upgraded metal seals. The final criteria list is as follows:

1. **Material should have a high modulus of resiliency at 700 K (800 F).**

   The modulus of resiliency is the area under the elastic portion of the stress-strain curve. This modulus is a measure of the ability of a material to absorb energy elastically. The equation for this modulus is: (Yield Strength)/(2 × Modulus of Elasticity). In one version of the recommended design, the seal material (without backup leaves) could be called upon to absorb the entire latch force. An important consideration, then, is high yield strength at operating temperature, which can also be an important factor in allowing an increase in amount of elastic deflection of the seal.*

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*Siegel, Martin J., "High-Temperature Springs", Machine Design, March 30, 1967.

Most seals normally operate in the range of 480 to 590 K (400 to 600 F), with the highest temperatures at the top of the door. Test work in Task 2 (the physical model) indicated that even a small fire at the seal would heat the seal to near 810 K (1000 F), although the temperature rise of the more massive door frame and jamb (with a small fire) was small. USS Research has reported on one example of seal temperatures climbing to 700 K (800 F) during the steam-aspiration period just before charging of coal to an oven. We selected 700 K (800 F) as the temperature at which the mechanical and physical properties of materials should be compared.

2. **Materials should have a low relaxation and creep rate at 700 K (800 F).**

Relaxation (loss of load carrying ability) is an important consideration in selecting materials for springs, but the amount of data on relaxation rate is rather meager except for some alloys. A literature search was completed looking for the recommended maximum continuous operating temperatures for various materials when used as springs. It was assumed that the technical personnel setting these upper-limit temperatures had experienced creep (dimensional change) or relaxation (loss of load) under heavy spring loads at temperatures higher than those specified. Some of the data taken from the literature are as follows:

Material	Maximum Continuous Service Temperature	
Carbon Steel	394 K	250 F(a)
High-Carbon Steel	422 K	300 F(b)
SAE 6150 Steel (Low Cr + Mo)	450 K	350 F(b)
304 Stainless	533–560 K	500–550(c)
17-7 PH, Age Hardened	588–616 K	600–650 F(a,b)
Inconel 600	588 K	600 F(b)
A28, Age Hardened	700 K	800 F(b)
Inconel X-750, Age Hardened	755–866 K	900–1100(b)
Inconel 718	977 K	1300 F(d)

(a) Carson, Robert W., "Flat Spring Materials", Product Engineering, March 1, 1965.
(b) Crooks, R. D., and Johnson, W. R., "Flat Springs Above 500 F", Product Engineering, February 18, 1963.
(c) Siegel, Martin J., "High-Temperature Springs", Machine Design, March 20, 1967.
(d) Moeller, R. H., "Coil Springs Above 400 F", Product Engineering, October 25, 1965.

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*In other possible versions of the recommended design, backup leaves could be used to lower the stress in the seal material, and/or some of the latch force could be shifted to the stop bolts. See page II-43.

3. **Material should be metallographically stable at maximum temperature.**

   With sufficient time and temperature, some change in metallurgical structure can be expected for almost any alloy. Some alloys change structure (and properties) rather rapidly above some temperature, whereas other alloys react more slowly and can tolerate occasional excursions through "maximum" temperatures. For demonstration work, it is considered best to start with stable materials. Other less-stable materials can be evaluated once a performance standard has been established.

4. **Material should have a thermal expansion coefficient about that of gray cast iron and steel.**

   As previously indicated, we have reservations relative to the high coefficient of expansion of 304 stainless steel (when this material is bolted down on a gray cast iron frame). Battelle researchers believe that they have seen indications of thermal buckling of S-shaped seals in operation. If the door frame and the attached seal expand about the same distance in coming to operating temperature, the level of thermal stresses will be favorably low.

5. **Material should have a high thermal conductivity.**

   The thermal stress level to be developed in a seal is a function of several factors, including the thermal conductivity of the material. The higher the thermal conductivity, the lower the stress level, all other factors being equal. Seals will continue to be cooled rapidly by rain, and seals will occasionally be heated on one side by fires. Under these conditions, higher conductivity material is favored.

6. **Material should be available in strip form now.**

   The availability of high-performance material in strip form is in many instances a problem. For some materials, it may be necessary to place a special mill order. Battelle researchers need readily available material for small-order purchases for test work in Task 5 and for possible demonstration work.

7. **Material should be easily formed, weldable with no problems, and heat treatable with no problems.**

   Most of the high-performance materials can be formed (but not as easily as 304 stainless) by working with annealed material which is then aged to develop high strength and high hardness. We have been told that welding and heat treatment with some materials represent "no problems", but we are concerned about (a) the complicated aging step required for some alloys, and (b) the possibility of warpage during structural transformations and upon cooling a rangy, elongated shape such as coke-oven seals. Evaluation efforts in this direction are in progress.

8. **Material should be adequately corrosion resistant in coke-plant service.**

A summary of data on various alloys as they relate to the above criteria is shown in Table II-1.

Material Recommendation

At this time, our recommendation for a first choice of material for Task 5 testing is Inconel X-750. This is the material normally used for long-time service over 590 K (600 F). It is available in various thicknesses from two suppliers. Information is being obtained on availability of long sheets or strips.

The testing of Inconel X-750 will be followed by testing of various types of precipitation-hardening stainless steels. It is possible that several alloys will be selected for comparative testing in any demonstration project. Discussions are in progress with technical personnel of alloy suppliers.

Research Outline for Task 5

The primary objective of Task 5 will be the design of a full-scale sealing system for typical 4-meter Koppers and Wilputte end closures. The drawings and supporting documents resulting from the design effort will be prepared to Level 2, Production Prototype and Limited Production, defined in MIL-D-1000A, 15 October 1975. End-closure components made to these drawings will fit existing end closures matching the drawings furnished by Koppers and Wilputte Companies as typical of 4-meter ovens. End closures which do not match these typical drawings will require that the battery operator and the vendor be responsible for modifying the drawings accordingly. Variations should not adversely affect the intent of the design in any way.

Various tests will be conducted of portions of full-scale seals made of recommended materials. The following are typical of the expected tests:

- **Relaxation Test**. This test will be directed at verification of the high resistance to relaxation claimed by suppliers of some candidate materials. A short length of full-size seal will be clamped in a fixture and deflected a predetermined amount. Fixture and specimen will be placed in an oven at operating temperature for 16 hours (one coking cycle). The specimen will then be removed from the fixture and checked for relaxation and creep. This test may be repeated several times (some at

TABLE II-1. COMPARATIVE DATA ON CANDIDATE ALLOYS FOR MANUFACTURE OF COKE-OVEN SEALS

Material	Maximum Continuous Service Temperature With Low Creep or Relaxation Under Load, K	Maximum Continuous Service Temperature With Low Creep or Relaxation Under Load, F	Index of Relative Modulus of Resilience at 700 K (800 F)(a)	0.2% Offset Yield Strength at 700 K (866 F), MPa	0.2% Offset Yield Strength at 700 K (866 F), Ksi	Coefficient of Thermal Expansion(b) 293–700 K (68–800 F), 10^{-6} m/m/K	Coefficient of Thermal Expansion(b) 293–700 K (68–800 F), 10^{-6} in./in./F	Thermal Conductivity at 700 F (800 F), w/m/K	Thermal Conductivity at 700 F (800 F), Btu/hr/ft^2/in./F
304 Stainless (present material)	533–561	500–550	1 (reference level)	124	18	17.8	9.9	20	144
Ni-Cu-Ti (present material)	350	450	4 est	172	25	13.8	7.7 est	32	220 est
17-7 PH, Age Hardened	588–616	600–650	23	896	130	12	6.6	21	150
A286, Age Hardened	700	800	12	620	90	17	9.6	20	140
Inconel X-750, Age Hardened	755	900	16	965	140	14	7.8	17	120

Material	Material Availability	Basic Price per Pound of Strip Material, $/lb	Corrosion Resistance	Hardness (Brinell)	Comments on Forming and Treating	Stability Comments
304 Stainless	Available now	$1.00/lb	High	160–200	Easily formed. Easily welded. No heat treatment possible.	–
Ni-Cu-Ti	Yes, as channel	0.40	Low	–	–	–
17-7 PH, Hardened	Yes – various sizes	1.25	High	400	Formable. Weldable. Complex heat treatment.	Not stable over 600 F
A286, Hardened	Some sizes	3.85	High	–	Ditto	Stable to 810 K (1000 F)
Inconel X-750 Hardened	Yes, various sizes but length may be a problem	5.00	High	290	Formable. Weldable. Complex heat treatment. Long-time heat treatment required.	Stable to 810 K (1000 F) and higher

(a) 0.2% offset tensile strength (at 800 F) was used in calculation (instead of yield strength) because of the availability of the offset data.

(b) Gray cast iron expansion at 700 K (800 F) is about 12.2 to 12.6 x 10^{-6} m/m/K (6.8 to 7.0 x 10^{-6} in./in./F).

elevated temperature) to span the initial high relaxation rate expected before the material settles into a long-term low relaxation rate.

- **Spacing Test**. This test will determine the effect of spacing or shimming (bowing) upon the deflection capability of the seal and will provide a measure of the maximum jamb warpage or bowing which can be handled by the seal. A length of about 1.2 m (4 feet) of full-size seal will be mounted in a fixture in a shimmed condition. Shimming will induce a bow of 1 mm (0.04 inch) in 1.2 m (4 feet) which is equivalent in terms of seal styles to a bow of 13 mm (0.5 inch) in 4.3 m (14 feet). The shimmed specimen will be forced against a simulated jamb seal surface of matching bow, deflected the design maximum, released, and checked to determine if the elastic limit has been exceeded.

  If, in the test described above, the elastic limit has not been exceeded, the seal will be reshimmed to increase the bow some discrete amount. This step can be repeated increasing the bow each time until the elastic limit of the seal is exceeded and permanent deformation of the seal can be detected.

- **Corner Test**. Battelle does not expect any severe problems with the corner. However, the length of seal used in the spacing test can have a fabricated corner attached to one end so that it deflects each time the spacing test is conducted. This arrangement will provide visual evidence that the corner does perform as expected. This arrangement can also be used to determine if the optional back-up leaf springs must be carried around the corner, as must the seal ring, or if they can be terminated at the corner at the point where the seal edge begins its curve.

The output of Task 5 is to include recommendations dealing with the following questions:

(a) Are backup spring leaves required?

(b) Will stop bolts be required to limit the loading (deflection) on the spring seal?

(c) Is it possible to design a single, leaf-spring seal that can absorb the entire latch loading with stop bolts only being used to protect the seal during the mounting of the door?

It is probable that the final answer for some of these questions will depend upon the results of any comparative testing tasks recommended for the demonstration project.

CHAPTER III

JAMB ANALYSES: RECOMMENDATION OF A RETROFITTABLE JAMB DESIGN AND JAMB MATERIAL

Introduction and General Statement of the Problem

In the context of this project, production of coke is a high-temperature, gas-producing process that is conducted in *brick* structures that are difficult to keep gas and vapor tight. The particular emphasis of this project is to develop upgraded and retrofittable end-closure components that will give long life and significantly improved emission-control performance.

The emphasis in this chapter of the report is on jambs. This major component of all modern end-closure systems exists in the field in ten or more cross-sectional "shapes". Six of these shapes are illustrated in Figure III-1. Although jambs are massive, they appear to be vulnerable to problems. Our interest in this project was to find out: Why do they warp or distort? How do jambs interact with buckstays and doors? What can be done to design and make jambs that are both retrofittable and more stable?

In the preceding Concepts Study, evidence of the jamb warpage was reported. It was one of the major conclusions of that study that "the door-mounted seals often receive the blame for coke-door emissions, but the fundamental cause of the emission-releasing gaps is the pronounced degree of warpage that has occurred in differing degrees on most (if not all) of the 25,000 or more cast-iron jambs in operation". Another related conclusion was that "existing seals were not designed to conform to more than a minor amount of jamb bowing and warpage". These represented generalized conclusions supported by observations and some measurements, but unsupported by any analytical effort or information useful for the design of upgraded jambs.

In the present project, our "jamb problem" was to:

(a) Develop an understanding (to the degree possible) about the fundamental reasons why and how designs and materials of existing jambs present problems in terms of their contribution to end-closure emission control. The recommended approach was an analytical effort supported by field measurements and by operation of a quarter-scale, heated physical model.

(b) Develop recommendations for a design of retrofittable jamb that would be more stable, both in the short and long term, and would perform in an improved way to give better sealing at both the back and the front sides of the jamb.

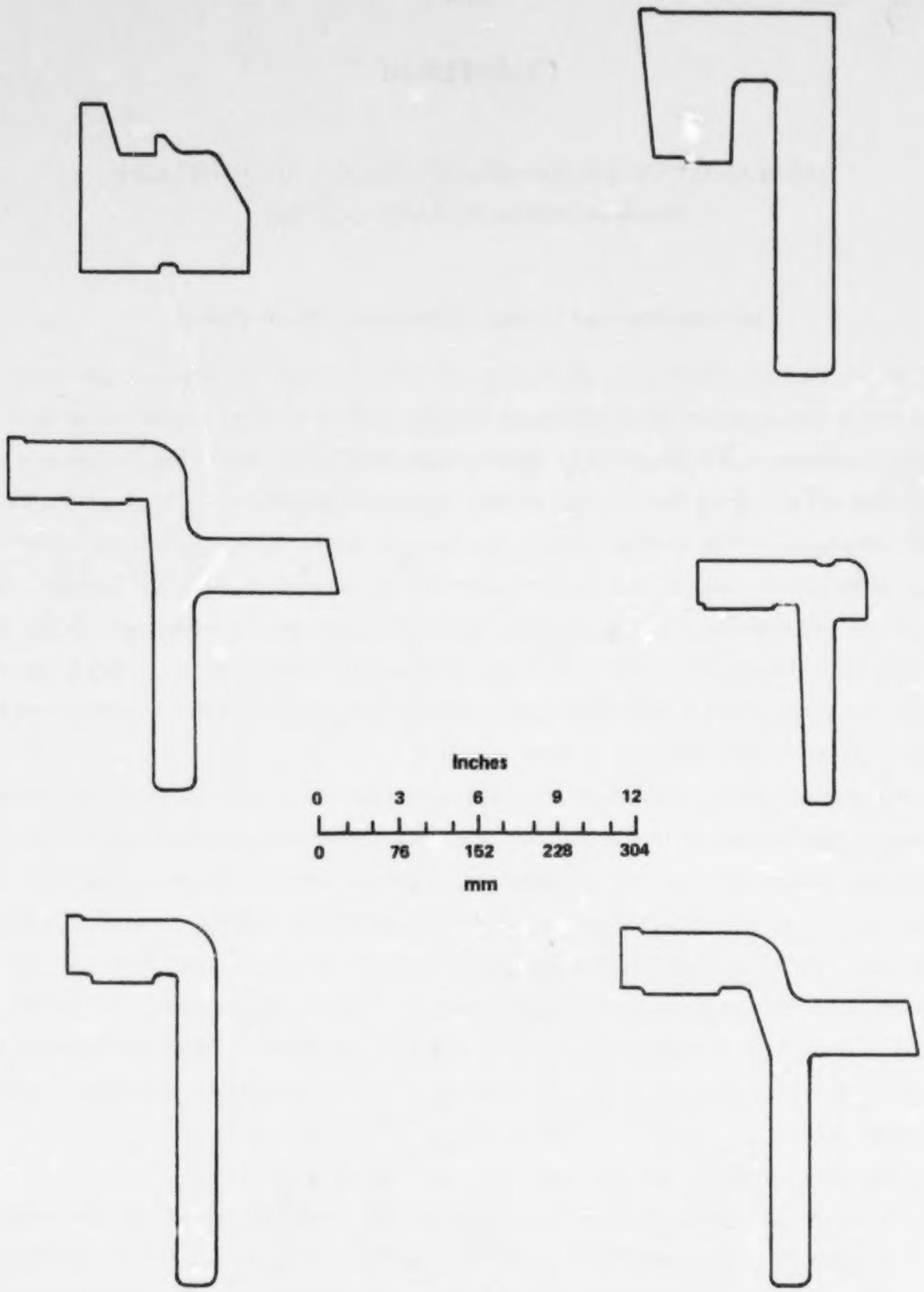
Inches
0
3
6
9
12
0
76
152
228
304
mm

FIGURE III-1. SIX EXAMPLES OF THE HORIZONTAL CROSS SECTION OF EXISTING JAMBS

The oven bricks are toward the top of the figure. The longer portion of the cross-section (shown vertically in five of the examples) is the jamb web or flange.

Data and Insights Obtained in Task 3 (Field Data Collection)

A detailed presentation of the data and information gathered in Task 3 is available to the Sponsors in a working paper summary that has been sent to them. This portion of the report discusses the highlights of Task 3 and serves as background material for the following sections dealing with analytical results and conclusions.

Long-Term Temperature Data on Jambs

At the start of this project it was reasoned that the warpage and distortions of existing coke-oven jambs may have been the result of past overstressing (thermal stressing) of this equipment under conditions that may well have only existed in the past. No coke plant keeps records of fires or records of any temperature data that can be related to dimensional changes in the end-closure components. To develop data for analysis, the field-team personnel wanted to start with new jambs and to obtain temperature and physical measurement data over a long period of time. This had the strong endorsement of coke-plant superintendents who believe that some significant portion of the damage to jambs occurs during the initial battery-heating operation. It was, therefore, decided to obtain temperature and strain-gauge data for new jambs on a new coke battery about to be heated, and on new jambs being installed as replacements on operating batteries.

At a new 6-meter battery, 39 thermocouples were installed in, on, and behind an unheated coke-side jamb prior to the installation of the jamb. In addition, calibrated strain gauges were installed on the latch hooks, jamb clips, and tie rods. Special data-acquisition equipment was also installed.

Unfortunately this data-collection installation was inadvertently destroyed by malfunctioning equipment during a pushing operation after only about 50 low-speed coking cycles. It was not possible to replace this sensing equipment, but it is hoped that some coke plant (with the possible support of the AISI) will attempt to obtain long-term data of this type. Battelle researchers consider this suggestion to be important, inasmuch as taller and taller coke ovens are being considered by steel companies and coke-plant builders.

During the short life of our installations, it was learned that:

(a) The temperature differential across "square" jambs (during coking cycles) was low in comparison to jambs having an exposed web or flange. The square jambs were partly embedded in the end bricks of ovens, so that only part of one face is exposed to convection and radiation cooling. Temperature gradients of only 1.3 K/cm (6 degrees F/inch) were measured on the square jambs, and gradients of 3.3 to 4.4 K/cm (15 to 20 degrees F/inch) and higher were measured on flanged jambs.

(b) During the early stages of preheating a battery, the top of jambs can be heated to as high as 780 K (950 F) if hot gases can leak out past the back of the jamb. This high temperature was measured during the period when the oven was being heated by firing through the door.

(c) Directing a stream of water at an end closure (simulating a heavy, slanting rain storm) can increase the temperature differential across a square jamb to 110 K (200 F) in less than 3 minutes. It took 3 minutes before the backside temperature began to drop. The longest time that water was used to extinguish any door fire was measured as less than 5 seconds.

Jamb Contour Measurements

At the beginning of this project, Battelle researchers were especially interested in measuring the vertical profile or contour of jambs. Our experience coupled with the evaluation of plant data indicated that many errors are possible in using measurement methods that depend on personnel taking readings while working on scaffolds or hoisting equipment. Our preferred measurement method for jam profiles was developed for shorter ovens using a relatively simple wire-referenced straight edge. We prefer this over taut-wire methods because the tool users only have to move the horizontal scales into contact with the jamb and then clamp the scales. The actual readings are taken at the bench level or off the bench after the tool has been lowered. The repeatability of this method has been established.

As noted in Chapter II, late in this project our interest shifted from measuring jamb profiles to measuring the horizontal spacing between the jamb seal-mating surface and the inboard side of the door frame (at attachment point for S-shaped seals). However, some jamb-contour measurements were taken at five batteries during this project. While this is only a small fraction of the batteries in operation, the results of our measurements (after the learning period) indicated that the degree of warpage to be expected in the field will not be so pronounced as we had expected from the plant data given to us during the Concepts Project. To elaborate further, most existing jambs were installed to remain straight. However, the thermal gradients across the jambs represent a force that is driving the jambs to take an inward-bowed shape (top and bottom of the jamb are further out from the battery than the center). Bowing was once considered warpage by the field team, but inward bowing later came to be considered to be natural. It was judged that bowing is only a problem if the seal cannot effectively contact the jamb. With this judgment, our research emphasis concentrated on ways and means for getting seals to contact *bowed* jambs. Fortunately, all but a few door frames take the approximate congruent bow of the inward bowed jambs. In a manner of speaking, we now consider jamb warpage as jamb profiles that an upgraded and more flexible retrofittable seal cannot contact and continue to hold in contact. We have been told that (a) there are jamb sides that have both an inward and outward bow on the same side (an S-shaped profile) but (b) these profiles are rare. In Task 5 the limits of adaptability of the recommended upgraded seals will be quantified. It remains to be seen whether shapes as unusual or as rare as S-shaped jambs can or cannot be accommodated by upgraded seals. It is expected that the percentage of jambs that will have to be replaced to achieve improved emission control on end closures may be small.

Movement or flexing of jambs during changes in thermal gradients (during coking cycles, during rainstorms, and during temperature excursions) remains an important consideration. The field team was not able to detect any amount of flexure nor were we able to confirm one steel company's data that there is jamb flexure during the period from "just before the charge" to "just after the charge". The fact that we could not detect flexure probably means only that we were not measuring before and after a significant gradient change or that we were taking measurements where the jamb was tightly restrained.* The force for jamb flexure is always present during a gradient change. If the jamb is not restrained, it must flex or change profile during a gradient change. Our approach to this possible problem was to place jamb-fastening methods and increased seal flexibility high on the research priority list.

Internal Damage to Gray Iron Jambs

Changes in microstructure of gray cast iron can be generally interpreted to indicate the range of temperatures to which the cast iron had been heated. However, the time and temperature relationships cannot be determined by this technique, because high temperature for a short time results in structural changes about the same as longer times at lower temperatures.

Examination of the microstructure changes in discarded jambs should have been a continuing task throughout this project. It was handicapped, however, by the low rate at which jambs are being replaced and the difficulty in cutting out cross-section samples.

From the examinations that were completed, the indications are that:

(a) The top section of the jamb (from the coal line up) continues to be the location showing signs of past overheating. Overheating is defined as heating to temperatures well over 700 to 760 K (800 to 900 F). These and higher temperatures result in weakening of gray iron and expansion of the gray iron due to graphitization and internal oxidation.

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*Jamb restraint is a variable at every end closure. No method was developed to measure this variable.

(b) signs of overheating of jambs show up first on the backside of the jambs, i.e., on the side of jambs facing the oven bricks. It was concluded that the "inside" fires referred to by coke-plant superintendents did exist, at least in the past. Whether "inside" fires have been eliminated is questionable because in some field trips batteries were observed to be "breathing". In these instances, fires at chuck doors would go out, restart, go out, and restart at regular intervals. This, however, may have been due to a repairable fault in the governor-house controls.

In the last part of this particular investigation, we attempted to answer the questions:

(1) Are there long-service jambs in existence that show no evidence of microstructural changes?

(2) If the answer to Question (1) is affirmative, is there less warpage of these jambs?

(3) If the answer to Question (2) is affirmative, is the door-sealing performance better than average?

Our search for such a battery took into consideration (a) battery age, (b) our general rating of the sealing performance, (c) our judgment as to whether the battery had been well maintained, and (d) whether or not it was a single battery or one of a string of batteries. This last consideration centers on the judgment often expressed by coke-plant superintendents that "it is easier to take care of and operate a single battery than a string of batteries". Our search resulted in the selection of a single 24-year-old battery having fixed-edge seals. This battery was just starting to replace coke-side jambs because of an occasional cracking problem.

Metallographic examination of samples taken from the next jamb that was replaced at the above battery indicated (a) no change in the microstructure of the of the gray cast iron after 24 years, and (b) a *trace* of a spheroidized (overheaded) zone on the backside of the jamb (top cross piece). It was inferred that coke batteries can be operated in a manner that does not result in heating of jambs to high temperatures—at least not for any long-time heating period(s). At this plant, the coke-side jambs have a slight outward bow [maximum 6 mm (1/4 inch) on those measured] and the steel door frames are unusual inasmuch as they also have an outward bow; i.e., the jambs and doors bow in the same direction. The end closures at this battery all release emissions when coal is being charged to the ovens, but each end closure is emission-free in less than 20 minutes. The door-sealing performance at this battery was, in our opinion, well above average.

In general, the work practices were not much different at this plant than at other plants, with the possible exception that the *workers* stated that they concentrated on "patching behind the jamb". In addition, they felt that hand troweling of refractory paste into the crack between the jamb and the bricks (and building up spalled areas on bricks) was much preferred to spray patching. In their operation they placed a heat shield in the open empty oven, climbed to the work site, and hand-pressed refractory paste into cracks using trowels.

Later in this project, Battelle researchers came to appreciate the difficulties involved in patching behind the jamb, particularly on 6-meter ovens. Another lesson learned was the large amount of patching required—at some plants it is a continuing program. Battelle researchers gave some consideration to improved patching methods and/or improved placement tools. These considerations are presented in a later portion of this chapter.

The Hourglassing Problem*

For Task 3, a special measuring tool was developed to follow the hourglassing rate of new jambs. The data obtained using this tool were as shown in Table III-1. Our periodic

TABLE III-1. COMPARISON OF THE AMOUNT OF HOURGLASSING OF TWO NEW 6-METER JAMBS OPERATED ABOUT THE SAME LENGTH OF TIME(a)

		Total Dimensional Changes from Original Measurements (Ambient Temperature) to Last Measurement at Operating Temperatures(b)			
Jamb Cross-Section:		"Square"		"Square"	
Jamb Material:		Ductile Iron		Unalloyed Gray Iron	
Jamb History:		Replacement Jamb		New Jamb on a New Battery	
Total Service Time at Last Measurement:		About 8 months		6 months	
Approximate Reference Location Above Bottom of Jamb					
Meters	**Feet**	**Millimeters**	**Inches**	**Millimeters**	**Inches**
6.25	20.5	+3.0	+0.12	+1.8	+0.07
5.6	18.5	+1.5	+0.06	+1.3	+0.05
4.9	16.0	–0.25	–0.01	–1.0	–0.04
4.4	14.5	–0.75	–0.03	–3.0	–0.12
4.0	13.0	–2.3	–0.09	–2.0	–0.08
3.4	11.0	–3.3	–0.13	–3.0	–0.12
2.7	9.0	–3.3	–0.13	–4.0	–0.16
2.1	7.0	–2.5	–0.10	–3.5	–0.14
1.4	4.5	–1.0	–0.04	–3.8	–0.15
0.2	0.6	+3.0	+0.11	+1.3	+0.05

(a) In the design of both of these end closures, there was no provision for locking the jambs to attempt to prevent hourglassing; i.e., the sides of the jambs were free to move toward each other.

(b) Measurements were between trammel marks indented in the jamb prior to jamb installation. The indicated distance changes are between the initial ambient temperature readings and measurements made on operating jambs after 6 and 8 months of operation.

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*Hourglassing has occurred when the midpoints of the two long vertical sides of a jamb have distorted towards each other so that these sides are closer to each other at their midpoints than at their ends.

measurements indicated that almost all of the hourglassing dimensional changes took place very early in the operational period of these jambs, i.e., there are indications that these jambs are now stabilizing. If this is happening, these particular jambs will not have an hourglassing problem.

In any demonstration project in which retrofittable jambs are tested, the changes in jamb dimensions will be compared with the data shown in Table III-1.

Conclusions (and Discussion) Derived from the Analytical Effort Dealing With Jambs

The detailed mathematical analyses and data summaries developed in Tasks 1 and 2 are available to the Sponsors in working paper summaries of these tasks. These working papers were presented without conclusions. This portion of this report deals with a descriptive presentation of the conclusions of the analytical work.

Background Comments

There are certain obvious reasons for the existence of jambs on coke ovens. The massive metal jambs in use on most batteries serve at least four functions as follows:

(1) Support for doors

(2) Provision of frameworks against which the latching forces can react

(3) Protection of the refractory-oven ends from the forces and loads involved in the pushing operations

(4) Provision of surfaces for the door seals to contact.

The Battelle team recognizes that jambs should serve these functions, but has reservations about the massiveness of the jambs in use on some ovens. There are also reservations about the way that some jambs are attached to ovens so as to interact with other components in unnecessary and possibly harmful ways.

If it is assumed that the above functions are the only functions a jamb needs to perform, then it is clear that the cross section of the jamb needs to be only strong enough to support the weight of the door and to react in an appropriate way with the seal to give a relatively uniform pressure around the seal. Because operators noted jamb warping and bending in the past, it is understandable that intuition would lead to the development of more massive and stiffer jambs. Intuition, however, can lead to erroneous conclusions. *This is particularly true when it comes to thermal action.*

Coke-oven jambs have a higher temperature on the back side against the bricks than on the exposed side. There is a heat flow through the jambs with an accompanying temperature gradient across the jamb. Because the hotter surface expands more than the cooler surface, there is an inclination for the jamb to change its shape. With the back side being hotter, the top and bottom of the jamb attempt to move outward away from the oven (provided that the center portion of the jamb cannot move inward). The above statements are true regardless of shape and dimensions of the cross section. The pertinence of the above discussion lies in the fact that the force needed to hold a jamb in place (i.e., to restrain flexing) depends upon the stiffness of the jamb. Stiffness refers to the resistance of the jamb to bending. As a generalization, the thicker a section in the direction of bending, the more difficult it is to bend and the more difficult it is to restrain it from thermal bending.

From this conclusion came the recommendation that the jamb cross section be no more massive than is necessary to perform its functions. Another favorable factor for shallower jamb sections (in the direction of bending) is that the overall temperature differential that results from sudden heating and cooling of jambs will be smaller, and therefore, the stress that develops during transient heat flows will be lower. No single numerical value can be placed on these design parameters, because they depend on the oven height, door weight, seal type, etc.

Of the four identifiable functions of a jamb, the most demanding is that of providing a surface for the door seal to contact. While this sounds like a simple passive task, it carries with it the implication of stability. That is, the sealing surface of the jamb should not move around significantly during a coking cycle or during any other operational sequence which it might experience

Analyses of Jamb Distortions

One of the approaches of the analytical team was to develop a numerical analysis of the factors controlling two types of permanent warpage of jambs. These distortions are (1) hourglassing and (2) the in-or-out displacements of the jamb sides relative to a natural or desired shape. Because almost all end-closure designs call for holding the jamb straight on the battery, in most instances jamb warpage was considered to be the bulges that deviate from the desired straightness.

The analyses performed on the jamb indicate that the mechanism for hourglassing is most probably creep accompanied with relaxation. In most jamb-attachment schemes, the jamb sides are free to move in the hourglassing direction. If the brickwork is rigid enough to restrain an outward bending of the jamb (in the anti-hourglassing direction) then the analysis showed that should creep or relaxation or both occur on either the inner or outer surface of the jamb, the result would be the classic hourglassing pattern. Basically, this occurs because the jamb *must* move, and it is free to move in only the one direction. A somewhat detailed analysis of this phenomenon led to the conclusion that the force required to restrain the jamb from hourglassing would be a relatively modest several hundred pounds. Therefore, it is recommended that the jamb sides be mechanically restrained (say, to the buckstay) to prevent hourglassing.

With regard to out-of-plane jamb warpage, no one mechanism has surfaced as the cause of this distortion. When this project started, several possible causes of jamb bowing were suggested. These included (1) brickwork expansion, (2) carbon buildup behind the jambs, (3) fires causing yielding of the material, and (4) structural changes within the metal of the jamb. To this list could also be added failure to adjust the jamb clips, bowing of the buckstays, and improperly adjusted latching forces. A few words can be said about each of these possibilities as they relate to the work on this project.

Brickwork Expansion. It is well known that brickwork in coke batteries expands with time. This growth can cause a problem relative to the stability of the end closure. Our analysis indicates that this expansion cannot be stopped by increasing the level of constraint. Any attempt to stop such movement would either be futile or would result in the permanent distortion of the jamb, the buckstays, the tie rods, or some combination of these components. The safest course of action is to make adjustments to the end closure to allow it to "ride with the expansion".

Coke-plant superintendents indicate that they attempt to operate batteries as steadily as possible; i.e., they attempt to minimize adjustment to the heating rate. Adjustments are required, however, and those that we know about concern changes in production rate, production interruptions, and slow downs during air pollution alerts. It is possible that unavoidable adjustments in the heating rate may have something in common with a problem that occurs at metal grain silos. Cyclic thermal expansion of the silo causes the grain to settle a little more each cycle, and then when the silo cools it becomes more and more highly stressed. It is not unreasonable to imagine a battery of coke ovens "breathing" in this fashion so that coal, coke dust, and tar can gradually work their way into small cracks during a "low-heat phase", and not allow them to close up on the next "high-heat phase".

Carbon Buildup Behind Jambs. The field team working on this project has reported that in some instances when jambs are replaced, the old jamb has a rather thick [up to 13 mm (1/2 inch)] deposit of hard carbonaceous material on the side of the jamb closest to the bricks. Some coke-plant personnel believe that the carbon "grows" and exerts pressure against the jamb. We have no explanation for a mechanism that causes swelling or expansion of existing carbon. However, the fact that the carbon layer gets thicker with time cannot be ignored, because operators have reported displacement of massive equipment (such as gas-main supports) which was alleviated by removing carbon buildup in connecting joints.

Our speculation is that jambs that have a rather thick back-side layer of carbon have been "breathing" or going through a ratcheting operation. Under conditions where the jamb-restraining clips are not tight, the jamb can flex during a change in the horizontal thermal gradient. This would open a gap behind the jamb, with subsequent clogging of this gap with tar. This tar converts to carbon by the loss of the lower-boiling-point constituents in the tar. This residual material can prevent the jamb from returning to its original position or profile. The jamb is now under additional stress which can exert more force at other clips. If this force results in jamb flexing, another gap is opened at another location, with the result that carbon is deposited behind the jamb at the other location. If the stress in the jamb is relaxed over a period of time, the jamb has a new permanent profile (i.e., warped), so that carbon buildup can continue provided the clips allow additional flexing of the jamb.

Our field team has indicated that (a) most superintendents are not happy with the strength of the jamb-restraining clips on the older ovens, and (b) some plants have "given up" on the plan of keeping jamb clips tight. It was concluded that weak or loose jamb fasteners permit jamb flexing and results in carbon buildup behind the jambs. This can contribute to jamb warpage. It is recommended that jamb-restraining connections should be upgraded on retrofittable jambs to minimize movement of the jambs both inward and outward.

Intense Fires. Fires can cause numerous problems on end closures, at least in theory. In Task 3, metallographic examinations of cross sections of discarded jambs showed that sometime in the past the upper portion of some jambs may have reached 920 K (1200 F). Discussions with operators revealed stories of jambs in a "cherry red" condition due to fires "behind the jamb". Other discussions suggested a general feeling that jamb warpage and sealing failure were, to a large extent, the result of fires along the seal/jamb and jamb/brick interfaces where visible leakage occurs.

It is reasonable to predict that should the jamb be subjected to thermal mistreatment, it will deform permanently. Moreover, if deformation should occur, it will aggravate the problem through more and larger fires due to increased volumes of combustible gases and vapors leaking past the seal. The ability of most common structural steels and irons to recover elastically from some load becomes less as the temperature of the material increases. Because of observed fires and the generally elevated thermal environment of the jamb in a coke oven, it is natural to blame this degradation in strength for much of the problem of sealing coke-oven end closures. Several results obtained on the physical model and in the analyses make this ready explanation much less "ready".

On the model, fires were considered as a possible cause of jamb warpage. However, the jamb is a rather large thermal sink. Fires occurring at the door seal tend to (a) lower the gradient through the jamb, i.e., lower the stress and (b) rapidly overheat the thin door-seal material. To obtain the large thermal gradient required to build up a damaging stress in the jamb (under restrained conditions), it is necessary to have an intense fire behind the jamb. A fire in this location requires (a) air passageways around the back of the jamb, and (b) a pressure inside the oven lower than the ambient pressure (including wind pressure effects).

It is expected that an improved seal on jambs (backside and frontside) will minimize both emissions and overheating problems. Fires at the seal should be put out to prevent overstressing of the door seal. Changes should be made in the steam-aspiration controls that would make it necessary to use extra human effort to keep steam aspiration in operation longer than a required length of time (e.g., steam valves equipped with timers).

In some pushes, it is difficult to shove the hot coke out of the oven in one motion. "Stickers" can "park" the hot coke (for a period) directly alongside the coke-side jamb. Measurements made in the field show that the rate of heat rise on the heated jamb surface is about 33 K per minute (60 F per minute). However, when these data were used in calculation, the temperature difference that developed even in 20 minutes was not large enough to cause stresses close to the yield strength. The simple fact is that coke cannot deliver heat to the jamb fast enough to develop large thermal differences *across* the jamb cross section.

Sudden Cooling of Jamb. To develop stresses high enough to cause yielding in a gray cast iron jamb, a temperature differential in excess of 110 K (200 F) must be realized through the thickness of the jamb. As noted above, back-side fires must be very intense to develop high temperature differentials. It seemed to the project team that if heat could not be supplied to the jamb fast enough to warp it, then perhaps heat could be removed at a rate fast enough to do damage. Although some coke batteries have sheds over the coke side, most batteries are completely exposed to rain. Tests were performed both on the model and in the field to measure the magnitude of temperature differentials which might result from a *hard*, inward-slanting, driving rain. In both test situations, the temperature differentials generated were higher than 110 K (200 F), and if the jambs were totally restrained from thermal bowing they would have yielded to some degree. The large differential is the result of lag in temperature change across the width of the cross section of the jamb. The maximum differential occurs at the time when the exposed surface has cooled and the back-side temperature just starts to fall as a result of the increased heat extraction. This differential can be minimized by reducing the cross section of the jambs. This recommendation is consistent with a previous recommendation dealing with the level of forces required to restrain thermally induced flexure of jambs.

Jamb Restraint Versus Jamb Stresses. For most end-closure designs, jamb restraint goes hand in hand with the development of thermal stresses in the jamb. What is wanted is firm restraint *and* low thermal stress. Low thermal stress can be achieved in two ways. The temperature gradient across the jamb can be reduced (as in the square cross-section jambs installed with only part of one face exposed to heat extraction), or the jamb can be installed so that it is allowed to take its thermally induced inward bowing once it is *at operating temperatures*. A jamb that is secured in position and has taken its "natural" heat curvature is practically in a zero thermal stress state. With this condition, any variation in temperature gradients gives rise to stress which varies about zero, instead of around some already high value. A practice that should be abandoned is that of securely attaching ambient-temperature, straight jambs to ovens and then allowing them to heat to operating temperature while preventing bowing. These jambs enter their operating life at a high level of thermal stress.

Late in this project the field team reported that a 4-year-old, 6-meter Koppers battery was in operation with the "allow the jamb to bow and then secure it" concept. We agree with this approach, and recommend it for retrofitted jambs on older batteries. Also reported were the facts that (a) the jamb web in the above battery was very deep, and (b) back-side patching appeared to be a problem with the "curved, stress-free" jambs. It will be recalled that we are recommending minimum-depth flanges on jambs.

There are various possible methods of mounting a jamb so that it is in a zero-stress condition when reaching operating temperatures. Late in project it was learned that Inland Steel Company is using a method that effectively achieves this result. As understood by Battelle researchers, Inland mounts the jamb and uses shims and mechanical force to bend the cold jamb to the shape that will be stress free when the jamb will reach operating temperature. After bending the jamb, the gap between the jamb and the bricks is grouted. After this grouting operation, the jamb is allowed to reach operating temperatures in preparation for service. In this instance, the jamb is stressed while cool, and as it heats the stress automatically slacks off. It remains to be established whether this approach can be adapted to other retrofit situations.

Jamb-Attachment Methods. The way that the jamb is held in place can be important to the effectiveness of sealing. Regardless of the particular design, nearly all jambs are held in place by reacting in some way with the buckstays. Some designs have a plate behind the buckstay, with the jamb attached to the plate by studs. In other designs, the jamb is either directly bolted to the buckstay or is clamped by means of clips which react with the buckstay. This last type of attachment results in what is sometimes referred to as a unilateral constraint. That is, the clips tend to keep the jamb from moving outward, but offer no resistance to the movement of the jamb towards the oven.

Because of the way jambs are held to a buckstay, the jambs gain all or a lot of the stiffness of the buckstay. That is, the stiffness of the jamb is effectively that of the jamb plus the buckstay. The measure of stiffness of a structural component is the product of the second moment of area and the modulus of elasticity of the material. Jambs considered in this study generally have a moment of area which varies from 60 to 700 in.^{4}, while the buckstays have moments which varied from 900 to 2500 in.^{4}. Now, if the jamb is held rigidly to the buckstays, and if the buckstays are so much stiffer than the jamb, it becomes apparent that the jamb can be effectively restrained from motion so long as the buckstay remains stable. Conversely, the jamb can "be at the mercy" of the buckstay should the top of the buckstay move away from the oven. Clips do not restrict any tendency for a jamb to hourglass.

It is recommended that the jambs be firmly attached to the buckstay (with special connectors) to prevent hourglassing and to minimize flexing of the jamb. With a locked-in-place jamb, it appears that the difficulties of maintaining a patching seal behind the jamb would be minimized. However, if the top of the buckstay moves outward, the top of the jamb will move outward the same amount. This would result in heavy leakage, carbon buildup, and other problems. It is, therefore, recommended that consideration be given to adding additional sealing strips that (a) are attached to the oven brickwork rather than to the buckstays, and (b) permit a sliding action with no gap development in the event the top of the jamb should move outward. A possible seal for this purpose is shown in Figure III-2. This approach assumes that carbon will not form in a gap (near the top of a jamb) that does not connect with the atmosphere, i.e., it assumes that it takes a flow-through to deposit tars in gaps.We do not know if this assumption is correct.

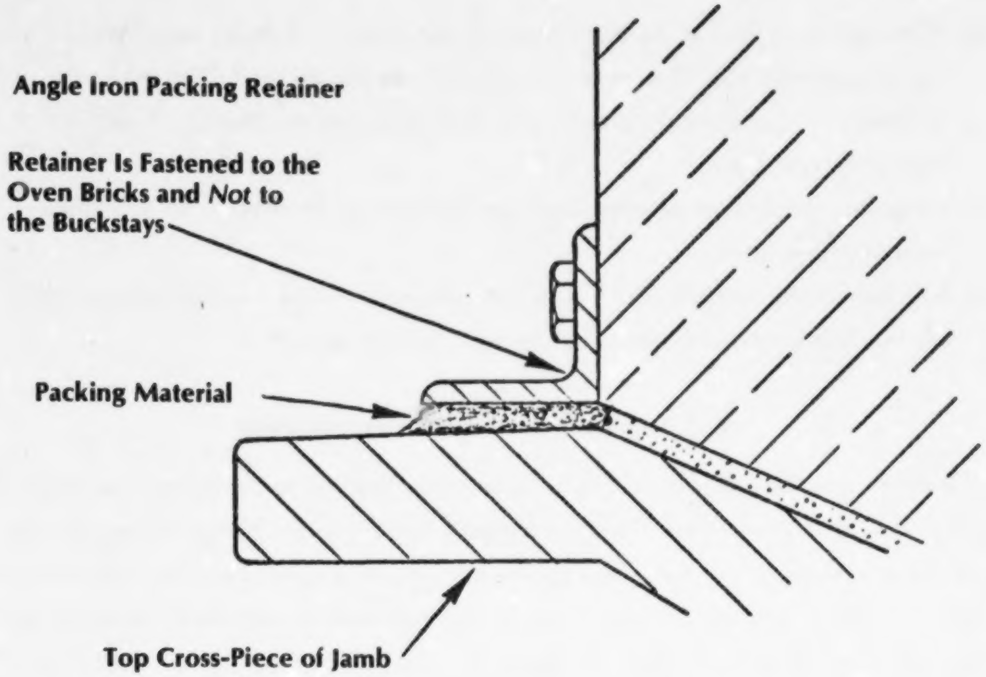
Angle Iron Packing Retainer
Retainer Is Fastened to the Oven Bricks and *Not* to the Buckstays
Packing Material
Top Cross-Piece of Jamb

FIGURE III-2. SIDE VIEW OF THE TOP OF A JAMB WITH A PROPOSED PACKING RETAINER

Summary of Recommendations for Retrofitted Jambs

(1) For retrofittable L-shaped jambs, lower the stiffness of the design by reducing the depth of the web section. This will make it easier to hold the jamb stable during temperature variations. This will also lower the temperature gradient developed during cooling of the jamb by rain.

(2) Mount the jamb so that it takes its natural thermal bowing without restraint when it is at operating temperature. This will help lower the stress level reached during any subsequent temperature excursions.

(3) In attaching the jamb to fulfill Recommendation 2 (above), fasten the jamb securely to the buckstay.

(4) In preparation for occasions when the top of the buckstay (and attached jamb) may briefly move outward away from the oven, design side seals that will allow jamb movement without opening flow-through gaps.

(5) Only elastic materials should be used for jambs. Gray cast iron is not elastic until such time as it has already taken a permanent set.

(6) Although small fires at the door seals do not result in damage to the jamb, they can damage the seal. The incidence of seal fires should be minimized by the installation of upgraded door seals, but such fires that do develop should be extinguished promptly.

(7) Minimize the length of time that any portion of an oven is at less than atmospheric pressure.

(8) For future coke batteries, serious design efforts should be directed to lowering of the operating temperatures of the end-closure components.

Jamb Material Selection/Recommendation

This portion of the report deals with the rationale that led to the recommendation to use annealed ferritic ductile iron for coke-oven jambs. The analytical effort on this subtask passed through various stages in response to the information and guidance received from the output of Tasks 1, 2, and 3. Because consideration of materials was not included in detail in Progress Reports, the reasoning that led to our recommendation is presented in some detail in the following paragraphs. The essence of the oral presentation made to the Sponsors on this subject is included in the summary of this section.

The Progression of Approaches Used in Material Evaluation/Selection

Because truly warped jambs obviously have been overstressed, the first approach was to search for materials which, for a minimum increase in cost, would have the highest ratio of

$$\frac{\text{Stress Tolerance at High Temperatures}}{\text{Stress Developed at High Temperatures}} .$$

While this search was in progress, it became appreciated that attempts to hold coke-oven jambs "straight" (on ovens) contributes to the warpage problem; i.e., stressing of jambs to force them to remain straight against their natural inclination to assume a bowed shape (as dictated by thermal gradient) was judged to be an approach to be abandoned in the retrofitting of jambs. At this point it appeared possible that pearlitic gray cast iron could continue to be used for jamb castings if heating above 640 K (700 F) for prolonged periods of time could be avoided. Above 640 K (700 F), unalloyed gray iron develops microstructural changes that can cause warping.

On further consideration, it was concluded that although securing of jambs on ovens only after the thermal bowing of the jambs has occurred would significantly lower the normal operating stress on the jamb, it would not eliminate stresses. Additional significant stresses could arise due to localized heating (e.g., door fires or fires behind the jamb) and also during the sudden thermal gradient increases that occur during rainstorms. Further investigation indicated that the stress tolerance and temperature resistance of gray iron could be significantly increased by addition of small amounts of alloying agents during the foundry process. At this point the researchers were discussing alloyed gray cast iron at progress review meetings with the Sponsors.

Later in the project, the analysts working on Task 1 (the mathematical model) and Task 2 (the physical model) were reporting that some of the highest levels of stress in jambs occur during the early cooling period that takes place during a slanting rainstorm. This rapid cooling causes a high, short-term increase in stress in jambs. The duration of the high-stress period is too short to result in significant creep or relaxation (these are time dependent), but the analysts and metallurgists began to request consideration of materials that have a true elastic range. Steel has an elastic range and ductile irons approach the elastic properties of steel. It is reasonably well known that cast irons (plain or alloyed) containing flake graphite do not have a true elastic range, and that they exhibit some *initial* plastic strain upon being loaded (either in compression or tension). Stated another way, cast iron parts upon being heavily stressed undergo a small amount of permanent dimensional change. In the case of coke-oven jambs, this could lead to warpage. *After* the first stressing, the gray iron will behave essentially elastically, unless the stress level later is raised above the original stress.

It was not appreciated how much this plastic strain (in the form of bowing) could be until prestressing (prior to machining the jamb) was considered as a method for minimizing the plastic component in gray irons prior to service. Depending on the strength of the cast iron and the length and thickness of the jamb, heavy prestressing would result in a bowing of from 5 to 13 cm (2 to 5 inches). This was considered to be out of range of practical manufacturing considerations and machining. These calculations were followed by laboratory tests in which water was sprayed against one side of samples of heated steel and cast iron. These samples were restrained from bending. Results confirmed the need for an elastic material as further insurance against the warping of retrofitted jambs. These results are covered in a later portion of this part of the report. Further consideration of gray irons was discontinued, and the consideration of elastic materials was started.

Basic Information and Evaluation of Jamb Materials

At the present time, the materials being used in jamb castings or jamb fabrications are (a) gray cast iron, (b) alloyed gray cast iron, (c) ferritic ductile iron, and (d) fabricated (welded) carbon steel. It is not clear whether various builders of coke plants are making specific recommendations to coke-oven operators about jamb materials, or whether the builders are asking the operators to make the selection. Judging from the comments of recent purchasers, some German builders appear to be recommending ordinary gray cast iron, and the Ikio Company of Japan (supplier of jambs, seals, and doors) is recommending gray cast iron alloyed with a low percentage of chromium to decrease the rate of microstructural changes in the contained pearlite. Some buyers have mentioned that the Koppers Company is recommending ferritic ductile iron, and operators of several older coke plants are replacing their cracked or warped gray iron jambs with fabricated steel jambs.

Late in this project visits were made to several relatively new 6-meter batteries including several Koppers-built batteries, one of which was equipped with gray cast iron and one with ferritic ductile iron. These jambs were originally installed to allow the jamb to take the curvature dictated by the thermal gradient. It became evident that the Koppers Company had developed the "let the jamb curve to hold down the stress level" approach well ahead of our analysis. Both the "curved" gray iron and ductile iron jambs appeared to have largely avoided dimensional distortions. However, the fact that the "curved" gray cast iron jambs on a new battery seemed to be dimensionally stable was not, in this instance, taken as an indication that curved gray iron jambs can be used in retrofit operations on older batteries. Our reservations with regard to this field information on curved gray iron jambs are based on the fact that the battery having this arrangement has unusually low temperatures on all of its end-closure components. This favorable and unusual condition is believed to be a function of the innovative end-flue combustion control installed on this battery; i.e., this battery is not typical in terms of end-closure conditions.

Thermal Stress Considerations. Given that metal is (a) being heated from one side, (b) in steady-state heat transmission, and (c) restrained from bowing; the basic equation for the stress on the outer "fibers" of the material (compression on the hot side and balancing tension of the cooler side) is usually given as:

$$\text{Maximum Stress} = \frac{\text{Elastic Modulus} \times \text{Thermal Expansion} \times \text{Temperature Difference}}{2} \quad \text{(hot to cold side)}$$

For our purposes the equation can be restated as:

$$\text{Maximum Stress} = \frac{\text{Elastic Modulus} \times \text{Thermal Conductivity} \times \text{Heat Flux} \times \text{Thickness}}{2}$$

If a simplifying assumption is made that the candidate materials all have the same thickness and are receiving the same heat flux into the back of the jamb, then the above equation can be used to rank the materials in terms of the relative maximum thermal stress developed. Our relative stress index is:

$$\text{Relative Stress Index} = \frac{\text{Stress Developed in Alternative Material}}{\text{Stress Developed in Gray Cast Iron}}$$

Using the foregoing equations and assumptions, the ranking of candidate materials is as follows:

Relative Stress Level Developed in Candidate Jamb Materials

Candidate Materials	Ranking Relative to Class 20 Gray Iron	Ranking Relative to Class 30 Gray Iron(1)	Nominal Price, Dollar Per Pound as a Jamb(2)
Class 20 Gray Iron	1.0	—	$0.40
Class 30 Gray Iron	1.4	1.0	$0.40
Alloy Gray Iron (0.8% Mo and 0.6% Cr)	1.8	1.3	$0.45–$0.50
Ferritic Ductile Iron(3)	2.8	2.0	$0.60
Carbon Steel	3.0	2.2	$1.30
Low-Alloy Steel (0.5% Mo)	3.8	2.7	$1.50

(1) Class 30 gray iron is usually specified for jamb castings. In some instances of early and rapid warpage of jambs, reports of investigation by steel companies indicate that they had received Class 20 gray iron instead of Class 30 gray iron. There was no information on whether the "rapidly warping" jambs had been subjected to fires, but the samples taken from the discarded jambs showed no indication of graphitization or internal oxidation. Class 20 gray iron exhibits a greater strain per unit of stress than Class 30 gray iron.

(2) Price does not include machining or any heat treatment. Shorter jambs carry a higher price per pound than taller jambs. Cost of fabricated steel jambs include the labor cost of fabrication.

(3) Only the ferritic grade of ductile iron was considered because pearlitic grades develop "growth" by graphitization above 800 F. This is another "safety factor" consideration.

If the only required viewpoint in material selection would be to find a material with the lowest level of developed stress, then low-tensile-strength gray cast iron would be the obvious selection. With the large amount of flake graphite in the low-strength iron, the modulus of elasticity is low and the thermal conductivity is high. There are, however, stress-tolerance considerations.

Stress Tolerance Considerations. There is available in the literature a considerable amount of information on the high-temperature mechanical and physical properties of the candidate materials. However, there is only a limited amount of stress-relaxation data; i.e., measurement of the reduction in stress under constant strain. Also, there are few data on compression creep or comparative thermal straining tests in which the magnitude of the stresses set up in the material depend to a large extent on the physical properties of the material; e.g., the expansion coefficient, elastic modulus, and thermal conductivity.

An ideal arrangement to obtain measured data as compared to calculated data would be to develop a laboratory arrangement in which it would be possible to obtain material dimensional changes (particularly with regard to bending) under conditions of:

(a) Varying degrees of restraint

(b) Varying degrees of heat input (and therefore temperature) to one side of samples, and

(c) Varying levels of thermal gradients, including water cooling of the unheated side.

Consideration was given to this approach but extensive testing of this type was not included in our proposal and work plan. Therefore, only limited testing was done by quenching restrained and heated samples. The results are presented later in this section.

In our search for upgraded materials, discussions were held with technical personnel in companies manufacturing diesel engines. These companies wish to keep material costs as low as possible, but they do have heat input to one side of gray iron (as in the cylinder heads) and the parts are restrained. Engine parts are, however, water-cooled on one side and they do not reach the temperatures reached in warped jambs (as inferred from metallographic examination). It was judged that the papers of Baker and Pope* (1961) and R. Bertodo** (1970) were the most appropriate for examination from the viewpoint of selection of a material for coke-oven jambs. Baker and Pope heated cylinders of gray and ductile iron after locking them in place in a special testing machine having fixed end-blocks. The samples were heated slowly and uniformly, and did not, therefore, reflect the effect of thermal conductivity of the material. On heating the bars, the compressive forces were measured as a function of time and temperature. During the slow heating and hold period (thermal gradient was low), there was plastic strain that translated into tensile stress after cooling to room temperature. In comparing pearlitic ductile iron, alloyed gray iron, and unalloyed gray iron (tensile strengths not specified), the unalloyed gray iron developed the lowest compressive stress on heating but the highest residual tensile stress on cooling. In this work it was indicated that gray iron could be alloyed (1.4% Ni and 0.4% Mo in this instance) to have thermal-strain properties superior to the ductile iron and particularly superior to the unalloyed gray irons.

Bertodo published an article describing his evaluation of 166 heats of plain and alloyed gray cast irons for use in diesel-engine components. At various temperatures and loadings, compressive creep and relaxation tests were obtained on samples of all the materials. Also measured were expansion coefficients, the elastic modulus, thermal conductivities, and fatigue data. Although not directly stated by Bertodo, it appears that he was working towards increasing the strength and the creep and relaxation resistance of gray iron (by alloying) while attempting to retain the maximum amount of the low-thermal-stress-generation properties of gray iron (e.g., low modulus, and high thermal conductivity). One of his considerations was to minimize the increase in hardness to retain a more ductile matrix (to retain low-cycle fatigue resistance). Bertodo developed alloyed pearlite gray irons [0.4% Mo + 0.4% Cr or 0.4% Mo + 1.3%(Ni + Cu)] having a resistance to thermal stress 2.8 times that of ordinary cast iron. Both the plain cast iron and the alloyed irons were in the 276 MPa (40,000 psi) ultimate-tensile-strength class.

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*Baker, S. G., Pope, J. A., "The Creep, Stress-Relaxation, and Thermal-Strain Properties of Several High-Grade Cast Irons", Report No. 363, The British Shipbuilding Research Association, 1961.

**Bertodo, R., "Grey Cast Iron for Thermal-Stress Applications", *Journal of Strain Analysis*, Vol. 5, No. 2, 1970.

At this point in the project, consideration was being given to recommending alloyed gray cast iron for retrofittable jambs taking advantage of the ability of molybdenum additions to increase the creep strength and relaxation strength. Chromium additions were also considered necessary to increase the stability of the pearlite.

Material Elasticity and Thermal Shock Resistance. As previously noted, near the completion of Task 1 (mathematical modeling) the analysts were requesting consideration of more nearly elastic materials for the jamb application. The stress-strain data of some of the important candidate materials are shown in Figure III-3. The gray irons (even if alloyed) have a stress-strain plot curved almost from zero stress. On loading these materials (if they have not been prestressed), a small amount of permanent deformation occurs as shown in Figure III-4. Once the peak stress occurs, further deformation essentially stops and the gray iron then begins to act almost as if it were an elastic material. In comparison, steel can be loaded to about its proportional limit and will return to its original dimensions upon being unloaded. The nodular or ductile irons, with their graphite in spheroidal form, approach the straight stress-strain line of steel, at least to the 170 MPa (25,000) psi level of stress.

In Figure III-4, various percentages of permanent strain have been converted to equivalent bowing in a 4.3-m (14-foot) jamb. Although the plastic component of gray iron is well known, in this work it became apparent to the researchers that a small percentage of plastic strain in cast iron can translate to an appreciable amount of permanent bowing in a gray iron jamb.

Working from stress-strain data, calculation can be made (as shown in Figure III-4) of the possible permanent distortions that will occur during the "shake down" effect in a laboratory test. Tests were made on annealed gray cast iron and steel plates measuring 6 mm (1/4 inch) thick by 38 mm (1.5 inches) wide by 14 cm (5.5 inches) long. These plates and fixtures were

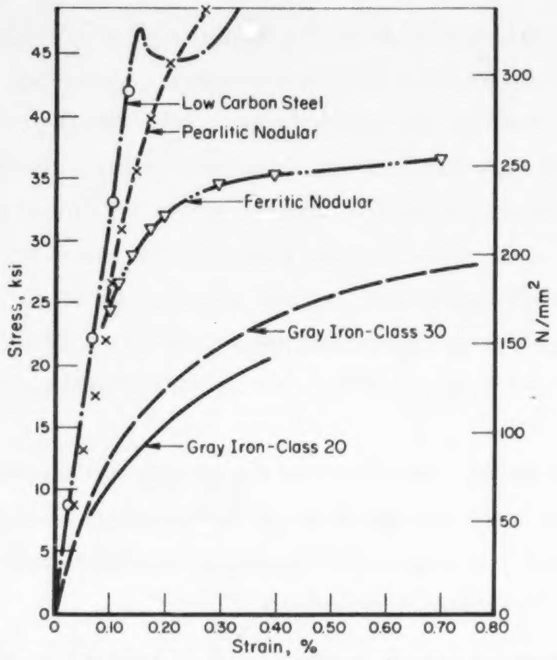
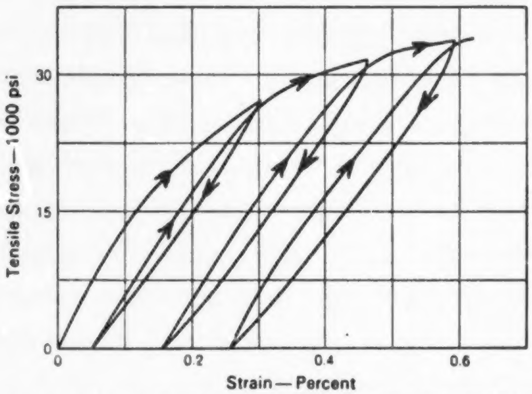


FIGURE III-3. TYPICAL STRESS-STRAIN CURVES IN TENSION FOR VARIOUS CAST IRONS AND STEELS



A stress-strain curve in tension for a class 30 gray iron in which the load was removed to show the permanent deformation^a.

FIGURE III-4. A TYPICAL STRESS-STRAIN CURVE FOR GRAY CAST IRON SHOWING THE AMOUNT OF PERMANENT STRAIN THAT DEVELOPS DURING THE EARLY STAGES OF PUTTING THIS MATERIAL IN LOAD-CARRYING SERVICE

Permanent Strain Percentages Converted to Amount of Bowing in a 14-Foot Jamb (6 × 6 In. Jamb)

	Equivalent Bowing	
Percent Strain	Millimeters	Inches
0.01	2.5	0.1
0.10	30.0	1.2
0.20	58.0	2.3

heated to 810 K (1000 F), and then were water quenched from one side as shown in Figure III-5. Typical results of several tests using different samples of gray iron and steel were as follows:

	Measured Bowing		
	Cast Iron		
Cycle Number	Millimeters	Inches	Steel
1	-0.25	-0.01(1)	None
2	-0.25	-0.01(2)	None
3	-0.25	-0.01	None
4	-0.25	-0.01	None
5	-0.25	-0.01	None

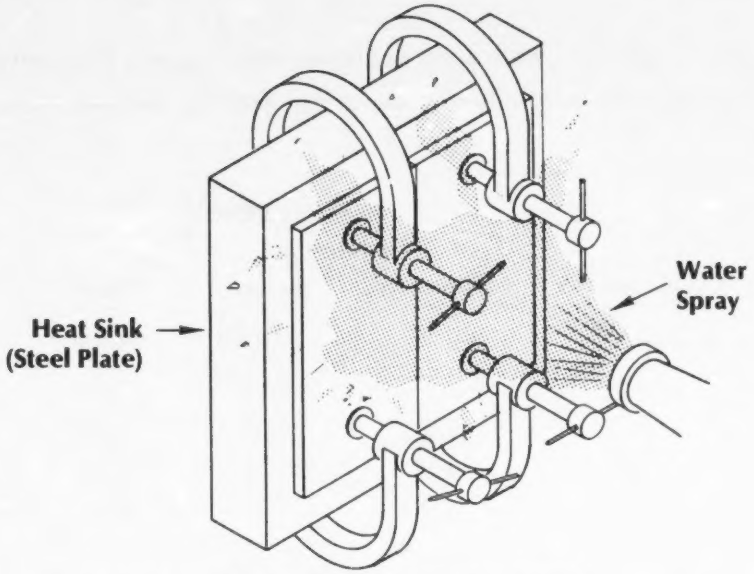
(1) Negative value. The cast iron samples took a permanent bow (as measured over the 5.5-inch length) in the convex direction, i.e., outward at the middle of the plate toward the the water cooling.

(2) There was no increase in bowing after the first cycle.

A bow of -0.25 mm (-0.01 inch) over a distance of 14 cm (5.5 inches) represents a permanent strain of about 0.2 percent (see Figure III-4). Depending on the length and thickness of a jamb, this could cause a bowing of up to 5 cm (2 inches). This test is considered to be rather drastic. However, the point of interest was that although the stress level on the steel samples had to be 2 or more times higher than in the gray iron (during the cooling step), steel did not develop a permanent set and gray iron did.

When gray iron jambs are replaced on operating coke ovens, in most instances the need for replacement is the result of cracks that develop after long periods of service. The replacement rate is about 5 to 10 times higher on the hotter coke side than on the pusher side. It is probable that this cracking is the result of tensile failure during thermal shocking of jambs during rain storms (and not due to water quenching of fires). Stress concentration and/or fatigue failure may also play a role. However, a change of material for retrofitted jambs was considered to minimize/eliminate cracking of jambs.

To be of most value, thermal-shock tests should rather closely approximate the operating conditions to be expected. A test procedure that is akin to the sudden cooling of the



Procedure:
1. Samples and heat sink are heated to 1100 F
2. After heating, samples are clamped to heat sink
3. Both samples are water sprayed on one side
4. After cooling, samples are unclamped for measurement of bowing

FIGURE III-5. LABORATORY ARRANGEMENT FOR SUBJECTING METAL SAMPLES TO THERMAL STRESS

restraining jambs was completed by Kattus and McPherson* in 1959. In their thermal-shocking procedure, notched cylinders of materials were subjected to a bending moment and were then heated evenly to 700 K (800 F) prior to water cooling to 340 K (150 F) in 15 seconds. The functions of interest were the number of heating and cooling cycles to fracture as function of bending load.

Their rating in terms of thermal-shock resistance was as follows:

		Approximate Stress Level to Obtain Cracking in 100 Cycles	
Ranking	**Material**	**MPa**	**Ksi**
1 (Best)	Steel	700	100
2	Ferritic Ductile Iron	350	50
3	Low-Alloy Gray Iron (0.6% Cr + 0.8% Mo)	300	40
4	Unalloyed Gray Iron [200 MPa at 700 K (30 ksi at 800 F)]	200	30

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*Kattus and McPherson, "Properties of Cast Iron at Elevated Temperatures", ASTM STP No. 248, 1959.

These results indicate that ferritic ductile iron and alloyed gray iron have more resistance than unalloyed gray iron to cracking under thermal-shock conditions, even though the thermal stress is higher in the steel.

Summary

Pearlitic gray cast iron has the advantages of:

1. Lowest cost
2. A high thermal conductivity and low modulus of elasticity, with the result that it (as a class) develops a relatively low thermal stress when operating under a thermal gradient.

Pearlitic gray cast iron has the disadvantages of:

1. Susceptibility to damage (internally) by temperatures over about 700 K (800 F)
2. Low resistance to creep and relaxation under load and heat
3. Tendency to crack in long-term coke-plant service
4. Inelasticity.

Pearlitic gray iron can be alloyed to minimize the first three disadvantages. Alloying will improve:

1. Resistance to structural damage by high temperatures
2. Creep and relaxation strength
3. Resistance to thermal cracking.

To a degree, upgrading of gray iron by alloying decreases both of the listed advantages. Alloying:

1. Increases the cost
2. Increases the elastic modulus and decreases the thermal conductivity

Because gray cast irons contain graphite flakes, nothing can be done to make gray iron a truly elastic material.

It is our recommendation that:

1. Annealed, ferritic ductile iron should be tested in any follow-on demonstration project. Steel has some properties that are improvements over ductile iron, but these improvements do not appear to justify the increased cost of steel jambs.
2. In retrofit situations, ferritic ductile iron jambs should be installed on ovens in such a way that the jambs have assumed an unstressed "thermal curvature" prior to final bolting. This method is being used by the Koppers Company.

It is our conclusion that annealed, ferritic ductile iron is the best compromise material for jambs when taking into consideration:

(a) Cost

(b) The need for a material whose elasticity approaches that of steel

(c) The need to eliminate jamb failure by cracking.

Concluding Comments

(1) *Annealed* ferritic ductile iron is recommended in order to bypass the possibility of having residual casting stresses in the jamb casting. Ferritic ductile iron can be produced (1) as cast (without following the casting operation with a ferritizing anneal) or (2) by a ferritizing anneal. It is recommended that tests be completed to confirm that sufficient residual stresses do not remain in as-cast ferritic ductile iron to cause jamb warpage. In a demonstration project, the two approaches to producing ductile iron jambs could be compared.

(2) The higher-strength ferritic ductile irons should be considered for jamb castings. If, during early trials, there is evidence of distortions that could be caused by creep/relaxation, it is recommended that the ferritic iron jambs in subsequent installations should be alloyed to increase overall stress resistance.

(3) The depth of the jamb web (or flange) should be decreased to minimize the high level of thermal gradients during transient heat input or heat-extraction periods. This consideration is covered in our recommendations on jamb design.

(4) As a generalization, the seal-mating surface of retrofittable jambs should have a surface as smooth as possible within the limits of reasonable cost. This recommendation can be explored during any demonstration project. The smoother the seal-mating surface of jambs, the easier it is to remove hardened tar (carbon) deposits.

Design Considerations for Retrofittable Jambs

The analytical team has indicated their requirements and preferences for upgraded jamb shape, performance, and jamb-attachment methods. However, in considering jamb retrofit, certain compromises must be considered.

While the analytical team prefers a compact "rectangular" cross section, economical retrofit of existing jambs *limits* the nature and degree of modification that can be applied to other end-closure components such as bricks, door frames, and latches. Modifications are also limited by operating clearances of components and by existing door-handling machinery. These limitations require that the jamb-seal surface and the jamb/brick surfaces remain unchanged on retrofittable jambs and that only the jamb flange or web can be considered for modification.

The jamb flange provides strength to resist latching forces through the latch hooks that are attached to the flange. The jamb must also absorb mounting restraints exerted through fasteners of various designs. As specified, attempts will be made to shorten the flange width on retrofittable jambs. There will be variations at individual ovens depending on the original design of the jamb.

Laboratory evidence suggests that smoother jamb-sealing surfaces would permit easier removal of hardened-tar deposits. This effect should be further investigated in the optional demonstration project. Many jambs have a roughness value of 125 microinches for the sealing surface. Finer surface finished should be tried, provided capability is available to produce finer finishes.

During Task 5 (Design and Testing) consideration will be given to jamb design considerations that might make it easier to upgrade the procedure for grouting behind the jambs. To be considered is the placement of grouting "ports" along the junction of the jamb sealing surface and the jamb web. Pressurized grouting may minimize some of the problems associated with back-side sealing. Some of the information developed during the development of sealing with applied sealants may be useful in this experimentation.

CHAPTER IV

AN ANALYSIS OF THE PROSPECTS FOR SEALANT SEALING (INBOARD LUTING) OF COKE-OVEN DOORS

Our definition of "prospects" for sealant sealing of coke-oven doors includes:

(1) Potential for emission control

(2) Potential for successful development

(3) Possible degree of acceptance by the coke industry.

Background and Definitions

Within the steel industry there are companies that routinely seal some 2000 coke-oven doors (on their older batteries) by a procedure called luting. In addition, there are foundry coke merchant plants that use this venerable sealing method. Luting consists of hand plastering the *outside* of the jamb/door interface with a low-cost water-tempered clay/coke mixture. This sticky mixture is applied before the coal is charged to an oven. In most instances, there is some release of emissions through or past the luting material. Following the completion of the coking cycle, removal of the door breaks the dried luting material. Fresh luting material is then applied to the closed door prior to the charging of coal for the next cycle. Figures IV-1 and IV-2 show the cross sections of two existing types of luted doors. Batteries that are designed to have luted doors do not use pressurized latching of the doors to the jambs. There are latches but they serve only to secure the door in position.

The emission-control performance of the luting operation is a variable depending on many factors. There is, for example, an element of skill involved in the preparation and application of the luting material. In one survey conducted by a large steel company, it was reported internally that "generally speaking, luted doors have shown no outstanding differences (in terms of emission control) than self-sealing (metal-to-metal) doors". One of the problems, for example, is that the mild combustion explosion that occurs when coal first enters an oven can jar and crack the luting material. In instances where these cracks and other points of emission leakage are repatched, the emission control can be good.

In visits to luted-door coke plants in the Phase I project, Battelle researchers had noted with interest that emissions do not come through the luting material after it has dried and become porous. This is a favorable consideration in terms of sealant development but, at the beginning of this project, this observation was tempered by the knowledge that the internal pressure in luted ovens is relatively low because of the shorter heights (older batteries) and

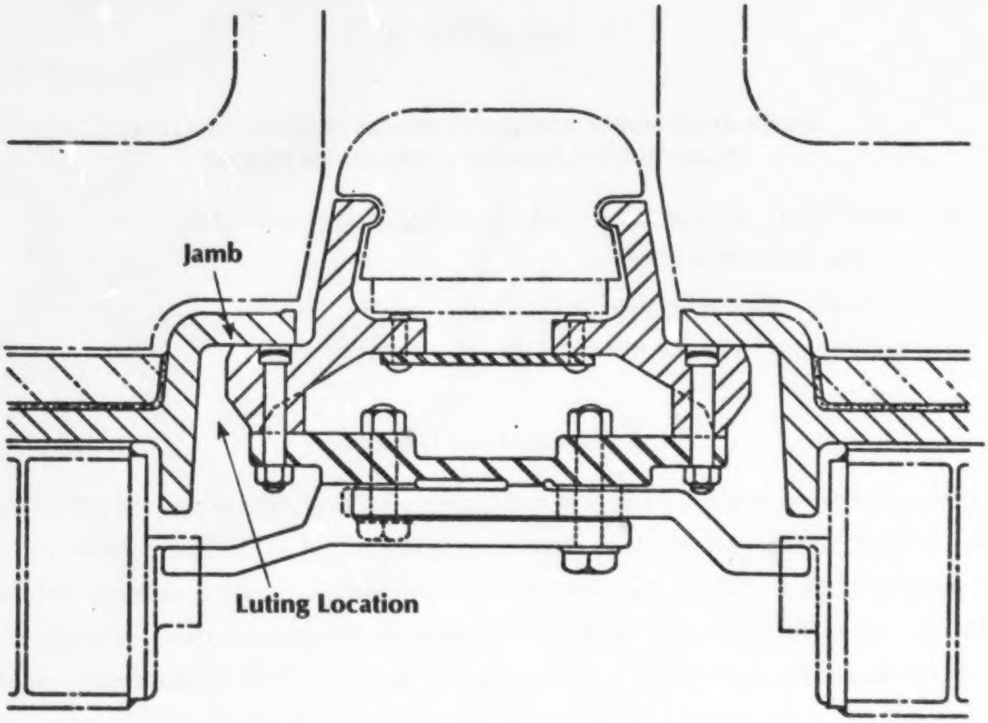

Jamb
Luting Location

FIGURE IV-1. LUTED DOOR DESIGN IN USE ABOUT 1946

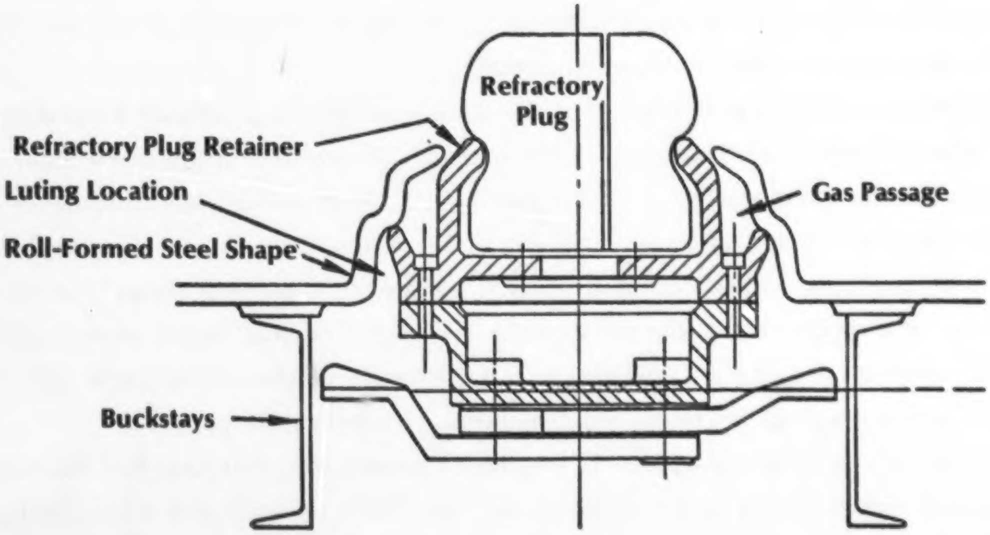

Refractory Plug
Refractory Plug Retainer
Luting Location
Roll-Formed Steel Shape
Gas Passage
Buckstays

FIGURE IV-2. LUTED DOOR DESIGN IN USE ABOUT 1929

longer coking cycles (lower temperatures). Also, the luting material in most instances dried very slowly. Thus the porosity does not develop in the material until the internal pressure peak may have already subsided.

Another element of background information is that a company has recently announced the intent to build a modern 5-meter battery (to produce foundry coke) that will be using the luting approach for sealing the doors.

Results of the Phase I Study

In our Concepts Study, variations of the luting approach were considered and evaluated (without experimentation or testing). Figure IV-3 is an example of one of these concepts. At the time of the report on that study we were thinking of a foamed-in-place sealant, including mechanized means to apply foam to the door while it was off the oven. Implied in our concept was (1) compression of the sealant on mounting the door, (2) one-time use of the sealant, and (3) mechanized methods of rapidly placing the material.

As part of the Concepts Study, members of the EPA organization and the AISI Task Force were asked individually to rank the various concept groupings. This ranking was done by working with a criteria listing and a weighting system developed with the cooperation of the EPA and AISI representatives. Both the EPA and the AISI members ranked the sealant concept as being the best (by a small margin) of all the concepts considered. The higher ranking for the sealant concepts was based on their higher rating for "effectiveness to reduce emissions". It was indicated that concerns over "operating cost" and "availability of materials" kept the sealant family of concepts from being rated best by a significant margin.

In Battelle's subsequent estimate of our level of confidence for successful final development and performance of each concept family, sealants were ranked below metal-to-metal sealing concepts. Our reservations were primarily in the areas of (1) increased gap-closure capability, and (2) dependability and repeatability.

It was Battelle's recommendation (in the Concepts Study) that "because sealing systems based on sealants have the possibility of completely eliminating door emissions, it is recommended that a laboratory/plant exploratory experimental project be initiated to further define the problems and possible solutions. It is suggested that, if there is demonstrable progress, the entire approach should be evaluated in a feasibility/cost/benefits analysis relative to the progress being made in the development of metal contact seals".

In the *proposal* for this present project, it was stated that:

(1) The "unknowns" that surfaced in the evaluation of sealant systems in the first study should be studied in a laboratory research project

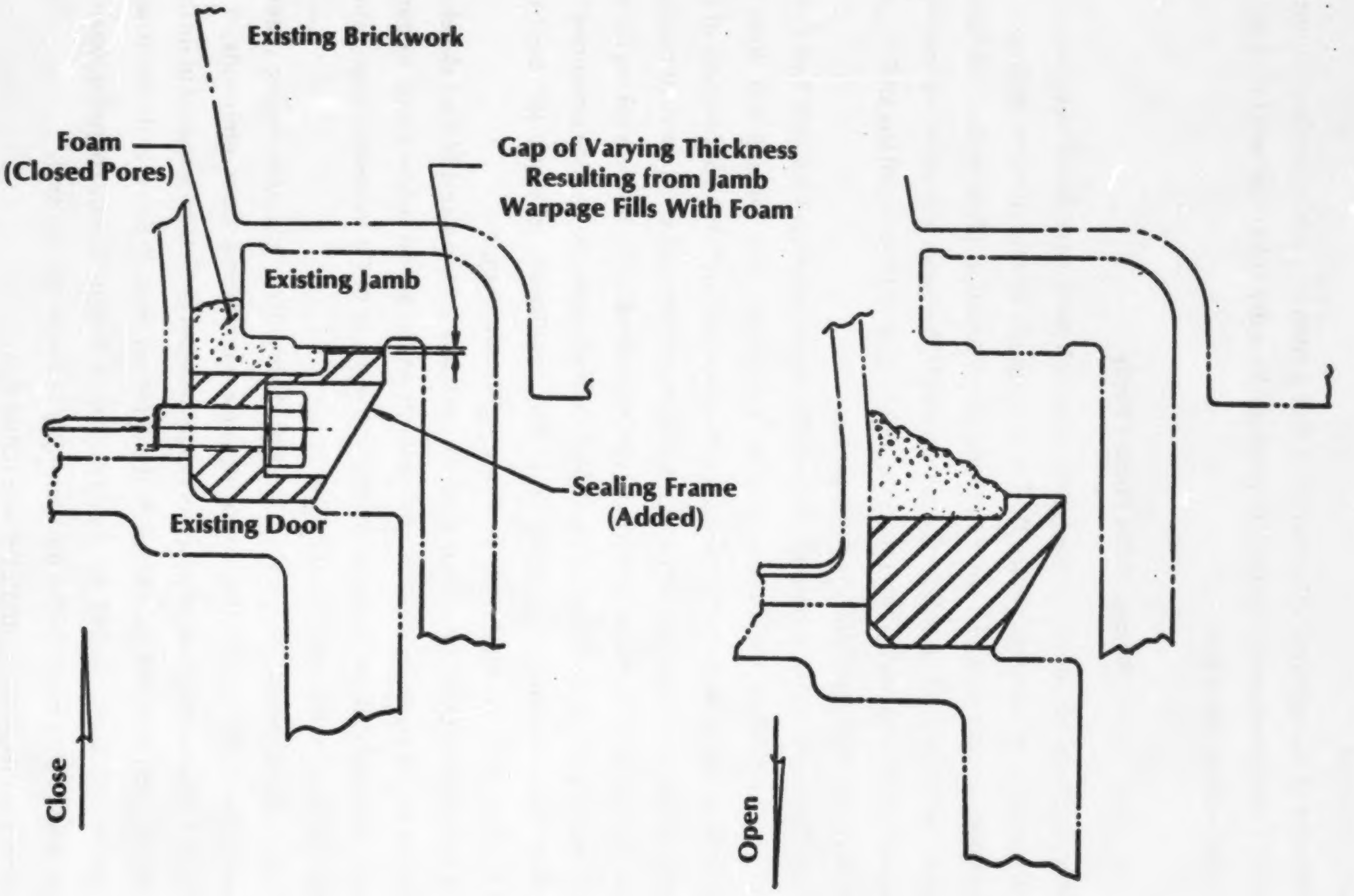

Existing Brickwork
Foam
(Closed Pores)
Gap of Varying Thickness
Resulting from Jamb
Warpage Fills With Foam
Existing Jamb
Sealing Frame
(Added)
Existing Door
Close
Open

FIGURE IV-3. AN EXAMPLE OF A SEALANT-SEALING CONCEPT PRESENTED IN THE FIRST PROJECT (STUDY OF CONCEPTS)

(2) Laboratory testing of sealant systems should be followed by a preliminary evaluation of candidate sealants at chuck doors

(3) A feasibility/costs/benefits analysis of sealant procedures will be completed as part of Task 4 (if there has been demonstrable progress)

(4) Because there is more uncertainty in terms of the potential for successful development of sealant systems, the expansion of a possible successful research project on sealant systems into a demonstration project is *not* included in this proposal.

This proposal was accepted by our Sponsors and this chapter of our report summarizes the work that was done on sealant research. Details were presented in the working-paper reports that have been issued to the Sponsors.

Criteria Development

To guide the research project on sealants, a list of criteria was developed. This list was expanded during the project and the final listing stated that an acceptable sealant should be:

(1) Low in cost per door closure (high-priced sealants can be considered provided that the sealants are reuseable)

(2) Tolerant of short-term heat excursions to 700 K (800 F)

(3) Capable of sealing up to a 6-mm (1/4-inch) gap between the door and the jamb without any "blowout" by the internal gas pressure.

(4) Resistant to attack from solvents and tars evolved by the coals

(5) Completely inert and should not evolve toxic or obnoxious fumes or fumes that create an environmental problem

(6) Expandable under the action of heat, or it should not shrink or crack (a) upon drying, (b) during the duration of the coking cycle, or (c) during a temperature excursion

(7) Capable of preventing leakage of emissions (particulates and gas) at all times—wet or dry.

If the sealant is applied as a slurry or mastic it should:

(1) Adhere to a vertical steel or cast iron surface operating at 530 K (500 F)

(2) Dry slowly to allow time to place the sealant and compress the soft sealant on latching the door

(3) Lose its adherence after drying so that when the door is removed the used sealant either falls off or is easily stripped

(4) Remain cohesive after drying and not create a dusting problem after drying or after use.

The criterion that specified that the sealant should be gas tight was selected as an ideal condition or goal. Battelle personnel were aware that every charge of coal evolves its own sealants in the form of condensible tars and vapors. If this specification could not be met in the laboratory, it was expected that field tests would determine whether the evolved coke-oven tars would seal the applied sealant and when this would occur.

Summary of Laboratory Results

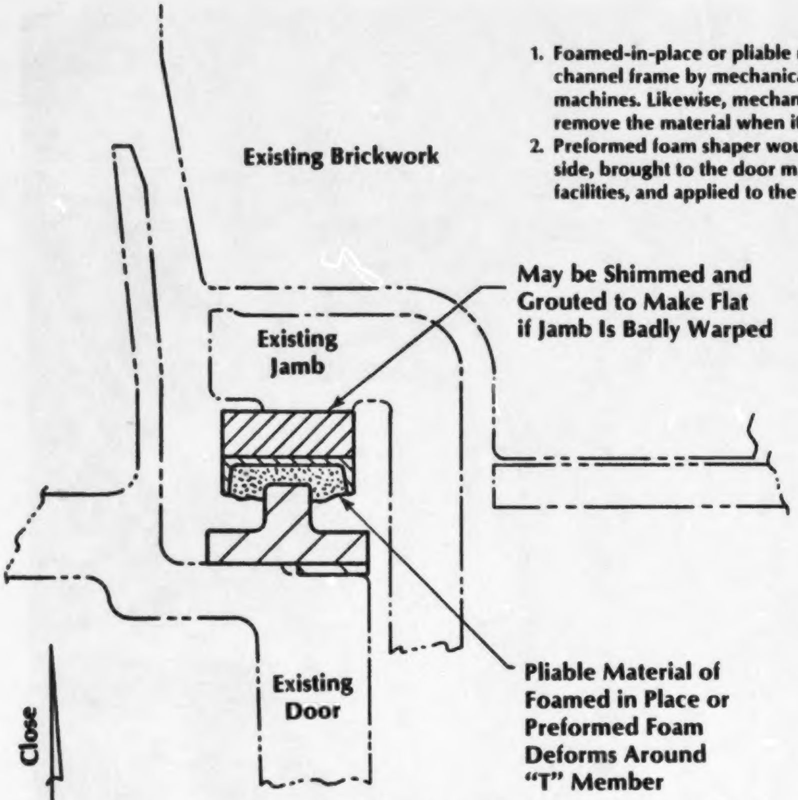
In the selection of laboratory test equipment, it was judged that more information could be obtained if a thin strip was used to penetrate or compress a contained sealant rather than compressing a sealant between two parallel plates. This approach is analogous to the concept shown in Figure IV-4 (taken from the Concept Study Report). To simulate this concept, a simple arrangement was built to evaluate material shrinkage, drying rate, and/or penetration resistance and release conditions. This simple equipment is shown in Figure IV-5. To evaluate gas tightness of both compressed sealants and sealants loosely filling a 6-mm (1/4-inch) gap, the equipment shown in Figure VI-6 was used.

A considerable amount of effort was expended in attempts to locate closed-pore foamed or unfoamed materials for use in the door-sealing application. All candidate sealants failed to meet two or more of the foregoing criteria. With this result, the research was shifted to development of a nonfoaming, nonshrinking sealant that would remain plastic for a 6-minute dwell period in the heated equipment shown in Figure IV-5. The 6-minute dwell period was selected as being about the maximum amount of time to be allowed for both placing the sealant and mounting the door on an oven. With the sealant still being plastic upon door closure, the door edge would penetrate the sealant to effect a seal. The following is a summary of the results obtained with various materials:

(1) Sixteen formulations were evaluated with fly ash as the base. The most promising ones had the following formulations:

	Volume Percent		
	Mix 19	**Mix 22**	**Mix 26**
Fly ash	40	46	53
Expanded perlite	40	30	53.6
Plastic ball clay	20	–	–
Corn starch	–	11	6.4
Pulverized pitch	–	13	–
Water	25	32	31

A small amount of sodium bicarbonate was added to some of the mixes to create early expansion and thereby improve retention in a channel during drying. Expansion was improved, but a layer of subsurface porosity was created at the metal interface.


Existing Brickwork
May be Shimmed and Grouted to Make Flat if Jamb Is Badly Warped
Existing Jamb
Existing Door
Close
Pliable Material of Foamed in Place or Preformed Foam Deforms Around "T" Member

1. Foamed-in-place or pliable material would be applied to the channel frame by mechanical means mounted on the door machines. Likewise, mechanical means would be required to remove the material when it is no longer functional.
2. Preformed foam shaper would be foamed at an off-battery side, brought to the door machines, stored in suitable facilities, and applied to the channel by mechanical means.

FIGURE IV-4. SEALANT APPLIED BETWEEN THE DOOR AND JAMB SURFACES (CONCEPT TAKEN FROM THE PHASE I REPORT)

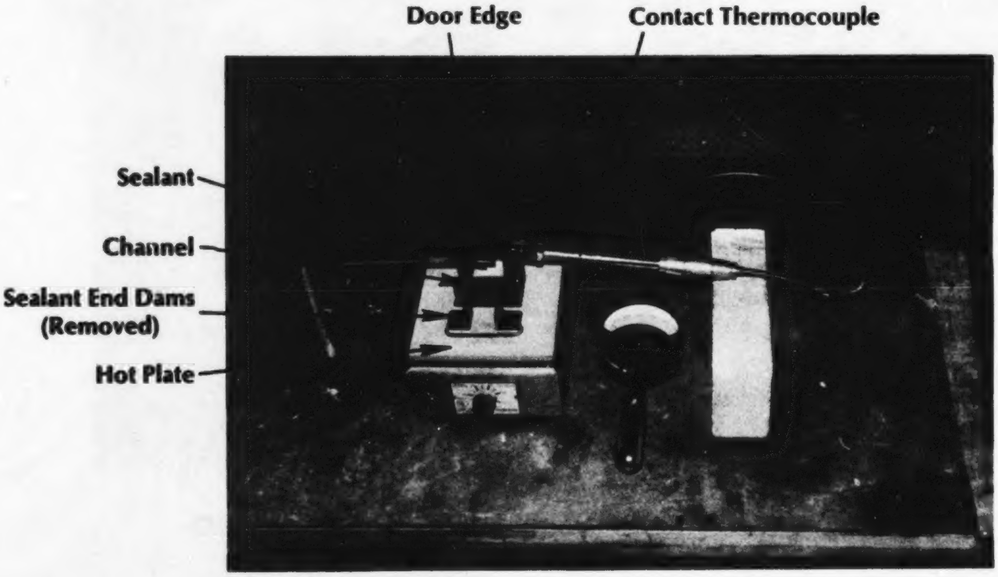

Door Edge
Contact Thermocouple
Sealant
Channel
Sealant End Dams (Removed)
Hot Plate

FIGURE IV-5. SIMULATED JAMB CHANNEL (DOOR EDGE EMBEDDED IN THE SEALANT)

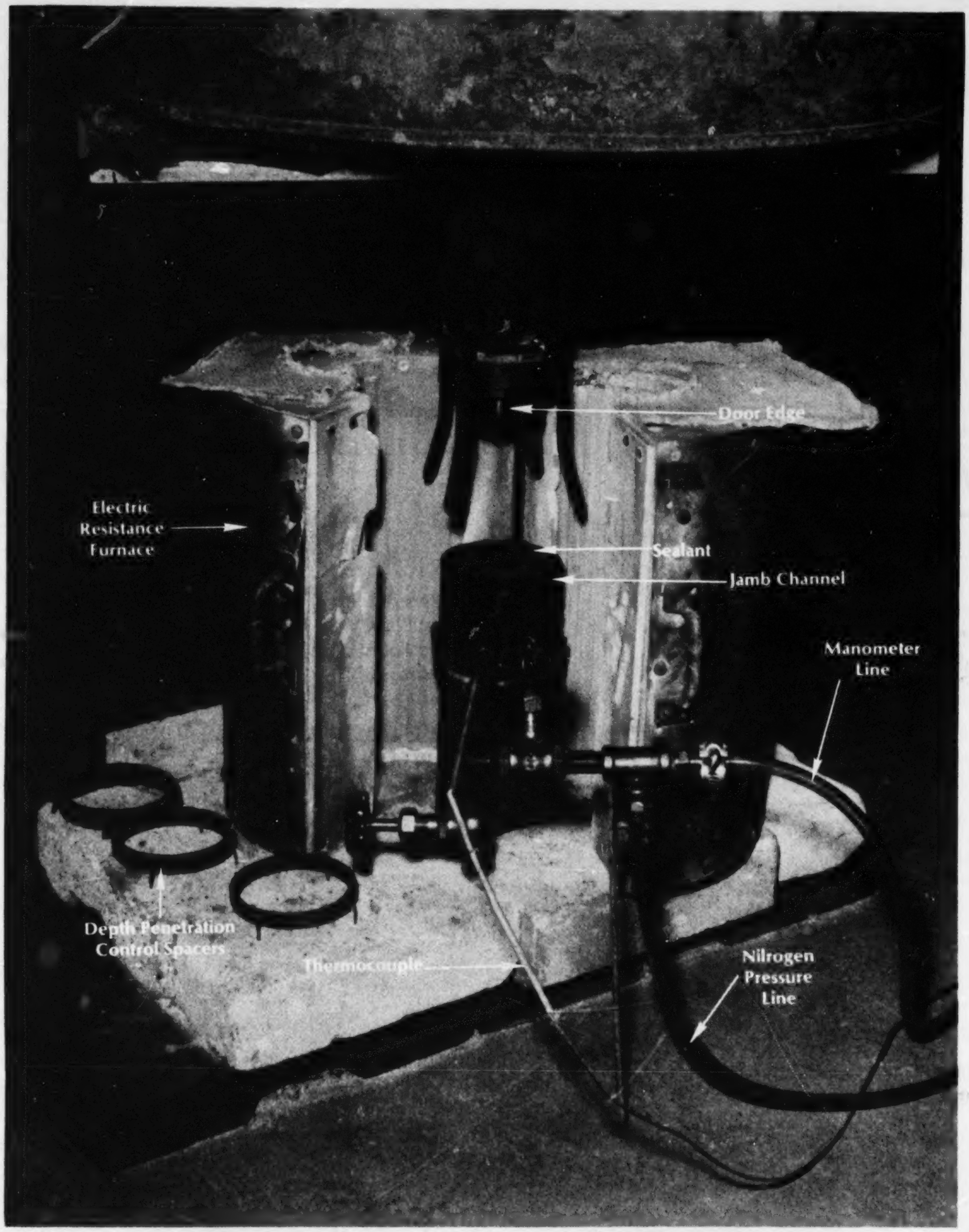

Door Edge
Electric Resistance Furnace
Sealant
Jamb Channel
Manometer Line
Depth Penetration Control Spacers
Thermocouple
Nitrogen Pressure Line

FIGURE IV-6. PHOTOGRAPH OF A LABORATORY ARRANGEMENT USED TO SIMULATE THE JAMB/SEAL RELATIONSHIP AT COKE OVENS

This equipment was used to evaluate the leak tightness (gas flow) of sealants when compressed between the seal and the jamb.

(See page IV-11 for comments on this equipment)

(2) Seven formulations were evaluated with minus 0.8 mm (minus 20-mesh) steel plant dust as a base. The base material consisted of waste in the form of basic oxygen furnace dust, blast furnace dust, dried blast furnace sludge, and mill scale in the proportions produced at the Kaiser Steel Corporation. All of the mixes were bonded with corn starch. Some had additions of expanded perlite or sodium bicarbonate. None of the mixes based on steel plant dust was judged to be acceptable.

(3) As a reference for sealant development, a quantity of luting material was provided by the Koppers Company which has a luted-door coke plant in St. Paul, Minnesota. This Koppers mix consisted of a combination of C&L clay (Cedar Heights Clay Company), coal, coke breeze, and water. As used in the test-channel arrangement, this mixture became hard and brittle in a 6-minute dwell period. Additions of expanded perlite or sodium bicarbonate resulted in good plasticity for 6 minutes but markedly increased the porosity. All variations of the Koppers mix gave a dirty release but none of them shrank on drying. The lack of shrinkage led to an evaluation of clays as a sealant base.

(4) C&L clay, without additions, was plastic after a 6-minute dwell period in a 420 K (300 F) channel, but shrank 17 percent. Upon reuse with some fresh clay, the shrinkage was lowered to 3 percent.

Western bentonite and Southern bentonite tested at 420 K (300 F) shrank 18 and 15 percent, respectively. Upon reuse of the Southern bentonite with some fresh material, the shrinkage was still high (13 percent). Plastic ball clay with an addition of some expanded perlite shrank 16 percent in a 420 K (300 F) channel. Reused C&L clay was superior to the bentonites in resisting shrinkage during drying. With 2 parts of used C&L clay to 1 part of fresh clay, an addition of 50 volume percent of coke breeze resulted in a small amount of shrinkage *only* across the top of a 420 K (300 F) channel. At 60 volume percent coke breeze, shrinkage was absent but the sealant was hard after a 6-minute dwell period.

From ancient times, potters have added carbonaceous materials to clays to reduce shrinkage on drying. It is apparent that the early developers of coke-plant luting material had known or rediscovered this effect.

(5) With a basic mix consisting of equal volumes of C&L clay and coke breeze in the proportions of 1 part used to 1 part fresh, additions of corn starch or expanded perlite with only 0.4 volume percent corn starch resulted in good plasticity, no

shrinkage, some debris on release, and scatter pores. In a 420 K (300 F) channel, the best composition with these ingredients was Mix 70:

2 parts of used Mix 69 (equal volumes of fresh C&L clay and coke breeze)
1 part fresh C&L clay
1 part coke breeze
6 v/o corn starch
25 v/o water.

In tests conducted at 530 K (500 F) it was found necessary to increase the amount of corn starch to retain plasticity for the desired 6-minute period. The mixture recommended for gas-tightness tests and field tests consisted of:

2 parts used material
1 part fresh C&L clay
1 part coke breeze
8 v/o corn starch
28 v/o water.

(6) Figure IV-6 shows a simulated door/jamb system that could be pressurized with nitrogen to evaluate the leak tightness of sealants after the door edge was embedded at a load of 13 kN per linear meter (75 pounds per linear inch). All of the sealant mixes tested became porous after drying and leaked gas. A review of recorded observations showed that all of the mixes showed evidence of veining at the hot-metal interface. The veins formed passages for leakage of the nitrogen.

(7) The cost of the materials in the sealant recommended for field trials was estimated as follows:

Mix	v/o	v/o of Dry Mix	Dry Mix Materials Cost		
1 p clay	50	100(0.5)/1.08=46.3	(1286 kg/m^3)(\$0.011/kg)(0.463 m^3/m^3 mix) =	\$ 6.55/m^3	
			[(180.3 lb/ft^3)(\$10/ton)(0.463 ft^3/ft^3 mix)/2000 =		\$0.19/ft^3]
1 p breeze	50	100(0.5)/1.08=46.3	(844 kg/m^3)(\$0.033/kg)(0.463 m^3/m^3 mix) =	\$12.90/m^3	
			[(52.6 lb/ft^3)(\$30/ton)(0.463 ft^3/ft^3 mix)/2000 =		\$0.37/ft^3]
8 v/o starch	8(a)	100(0.08)/1.08=7.4	(631 kg/m^3)(\$.209/kg)(0.074 m^3/m^3 mix) =	\$ 9.76/m^3	
			[(39.4 lb/ft^3)(\$190/ton)(0.074 ft^3/ft^3 mix)/2000 =		\$0.28/ft^3]
				\$29.21/m^3	[\$0.84/ft^3]

(a) Of the above.

Wet mix is about 80 v/o of dry mix; cost of wet mix is:

$$\frac{29.21}{0.80} = \$36.51/\text{m}^3\text{, or } \frac{0.84}{0.80} = \$1.05/\text{ft}^3$$

With clay at \$0.022 per kilogram (\$20 per ton) the cost is increased to \$45.20/m^3 (\$1.28/ft^3) of wet mix. Reuse of 1 or 2 parts of used sealant to 1 part of fresh sealant looks promising to reduce the cost. However, repeated reuse needs to be investigated to learn whether or not the starch content of the fresh portion needs to be increased to maintain the delayed hardening after the mix is applied to the hot door.

If the assumption is made that the industry will keep the machinery that slides the door downward a fraction of an inch prior to latching, then the channel at the top and bottom of the door needs to be wider than the channel on the sides of the door. For a door having a channel 2.5 cm (1 inch) deep, 51 cm (20 inches) across at the top and bottom of the door, 4.3 m (14 feet) on the sides of the door, and horizontal channels are 2.5 cm (1 inch) wide, and the vertical channels are 1.3 cm (1/2 inch) wide, the volume of sealant required is 0.0034 m^3 (0.12 ft^3). With clay at $0.022 a kilogram ($20 a ton), the indicated *material cost* for sealing a door is 15 cents. This is for a mix that consists of all virgin materials.

Conclusions of the First Phase of the Laboratory Work

(1) A near-standard luting mixture (clay and coke breeze), to which corn starch has been added to slow the drying rate, meets all of the selected criteria except that it is not gas tight after drying.

(2) It is recommended that a fresh mix of clay/coke breeze/corn starch/water be tested at a coke plant to determine whether the oils and tars evolved from the coals will plug the porosity that develops in the dried sealant.

(3) Of all the mixtures examined, the modified luting mixture (given above) will be the lowest cost per unit volume and per door closure.

(4) Luting mixtures containing corn starch give off a faint odor of burnt starch when heated to 530 K (500 F) and higher. In the field testing it should be determined whether this odor is detectable.

Summary of Field Evaluations

The major objectives of field testing a sealant were:

(a) Determine whether sealant (porous after drying) would prevent emissions, i.e., would the liquids evolved from the coal plug the "pores" of the sealant and prevent emissions in a usable length of time

(b) Determine whether gas leakage is actually blocked when emissions are not visible at the sealant location.

The sealant mixture taken into the field consisted of:

1 part minus 3.4 mm (6-mesh) coke breeze
1 part pulverized refractory clay (Cedar Heights Clay Company)
9 volume percent corn starch (of the above)
33 volume percent water (of the dry mix)

In weight percent this mixture consists of:

37.6 percent coke breeze
57.3 percent clay
5.1 percent starch
32.0 percent water (of the dry mix)

This above percentage of water gives a rather stiff sealant suitable for hand application with a putty knife. For the test, the jamb and door seal of a chuck door were scraped clean of carbon. This cleaning operation opened up gaps as much as 0.6 mm (0.024 inch) in width along the top and side of the closed chuck door. Just after the leveling operation, a thick layer of sealant was troweled only on the right top corner of the frame of the chuck-door housing, in line with the metal seal strip on the door. The door was then closed and the chuck door was observed during the first 30 minutes of the coking cycle. Emissions were observed from every location except where the sealant had been applied. The sealant dried slowly and the internal pressure of 59 Pa (0.24 in. of water) or higher did not force any visible emissions through the dried sealant. This was judged to be an encouraging result, but not necessarily a significant result. It was judged that duplication of the result at the bottom of a coke door (because of the higher pressure drop across the sealant) would, however, be a significant result.

To complete a test on part of an operating door, it was necessary to arrange for a known gap size (to be filled with sealant prior to closing the door) between the seal and the jamb, i.e., a manufactured gap. Consideration was given to placing a metal "spacer" in one of the lower corners of either a Koppers or Wolff-type door. Coke-plant superintendents, however, could not work up any enthusiasm for this approach. About this time it was learned that personnel of the Toledo coke plant of Interlake, Incorporated, were experimenting with an innovative seal consisting of a 2.5-cm-wide (1-inch-wide) asbestos braid. This plant was visited and permission was obtained to test sealants. Interlake, Incorporated, furnished a drawing of this seal (Figure IV-7).

By removing some of the adhered and hardened tar on the inboard face of this seal, we were able to develop a 3-mm (1/8-inch) depression or "gap" over a length of 15 cm (6 inches) at the left-hand bottom corner of the door.

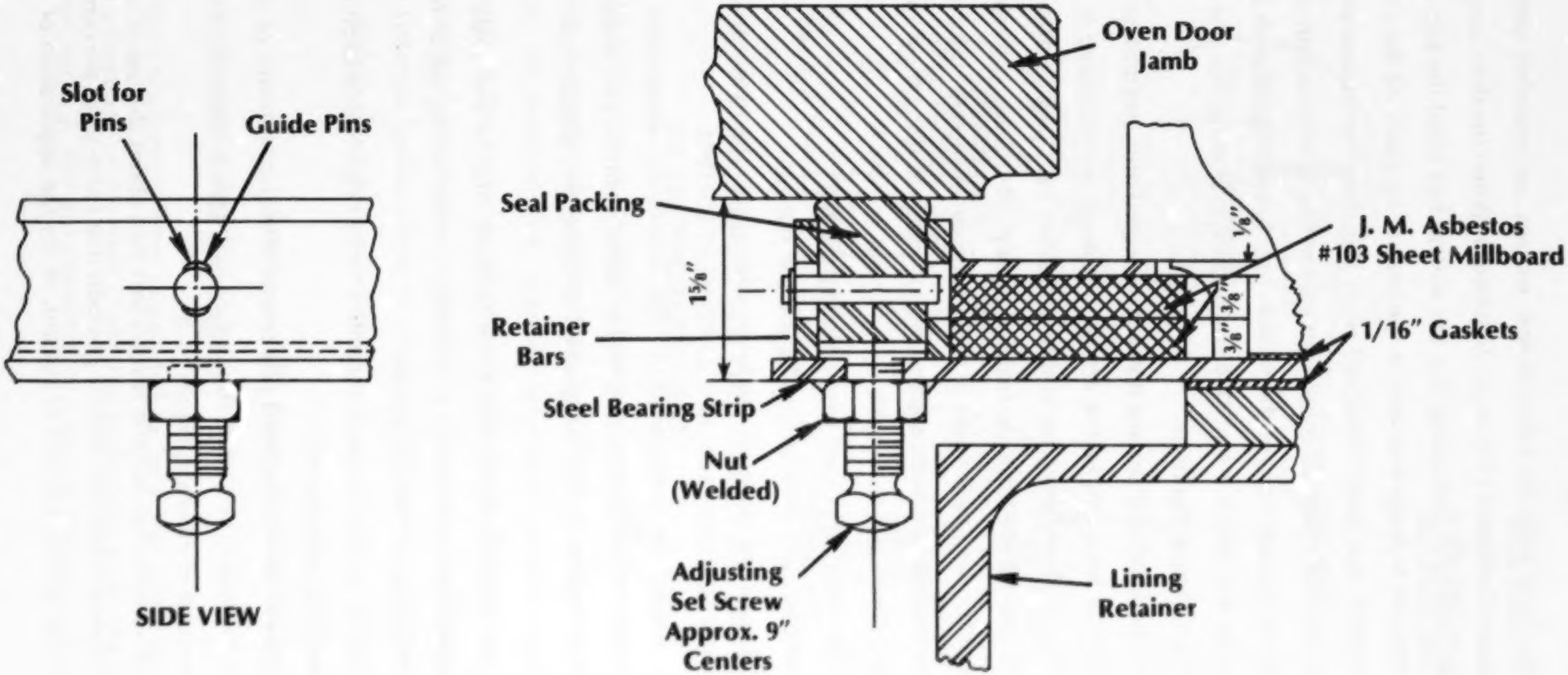

Slot for Pins
Guide Pins
SIDE VIEW
Oven Door Jamb
Seal Packing
J. M. Asbestos #103 Sheet Millboard
1/16" Gaskets
Retainer Bars
Steel Bearing Strip
Nut (Welded)
Adjusting Set Screw Approx. 9" Centers
Lining Retainer
1⅜"
⅛"
⅜"
⅜"

FIGURE IV-7. INTERLAKE INCORPORATED DRAWING OF A PROPRIETARY DOOR SEAL, I.E., A MODIFIED FIXED-EDGE SEAL

Adjusting set screws are in addition to the standard adjusting bolts.

Just prior to latching the door with the asbestos seal, sealant was troweled onto the inboard seal surface in the area of the 3-mm (1/8-inch) depression. When the door was latched, excess sealant was forced out sideways, indicating that the sealant had filled the gap area. On the next coking cycle, no emission leakage was seen at the sealant location. At the end of the coking cycle, the "used" sealant was easily removed from the door for examination. The sealant had hardened in use and had changed color from gray to black. Microscopic examination indicated that the pores or gas passages in the sealant had been plugged with tars. The portion of the sealant removed was about 3-mm (1/8-inch) thick indicating that the gap had truly been filled with sealant on closing the door.

In a second experiment, the localized sealant test was repeated and, in addition, sealant was plastered on the seal at other locations where emission leakage was observed in the first coking cycle. In this experiment, there were no visible emissions from any location where sealant had been applied. To test for possible gas leakage, a torch flame was directed at the seal area at 15-minute intervals for the first 2 hours of the coking cycle. No combustion could be initiated in any area where sealant had been applied, but other areas along the door did ignite. No odor from the heated starch was detectable.

It was concluded that these were significant experiments and that:

(1) Sealants prevent emissions even after becoming dry and porous.

(2) The tar from the coal seals the pores in the luting material to the extent that it prevents gas leakage.

(3) Additional research should be completed in the laboratory equipment to evaluate the performance of sealants with a higher water content, i.e., sealants that are either more pumpable or can be sprayed or flung into position on the door.

(4) Experiments should be completed to determine to what degree wet sealants thermally shock a heated cast-iron jamb; i.e., investigate whether the use of wet sealants could cause cracking of cast iron jambs.

(5) The approach of pressing a door or jamb-mounted knife edge into a channel filled with sealant should be abandoned.

(6) Emphasis should be placed on mechanized placement of sealant inboard of existing seals on coke-oven doors; i.e., apply the sealant in the gas passage depth in the seal area. This approach is shown in Figure IV-8.

Of the many original reservations that Battelle researchers had about the use of sealants on coke-oven doors, a major concern was the realistic position that some small percentage of doors would (a) not be given the proper amount of sealant, or (b) the application of sealant

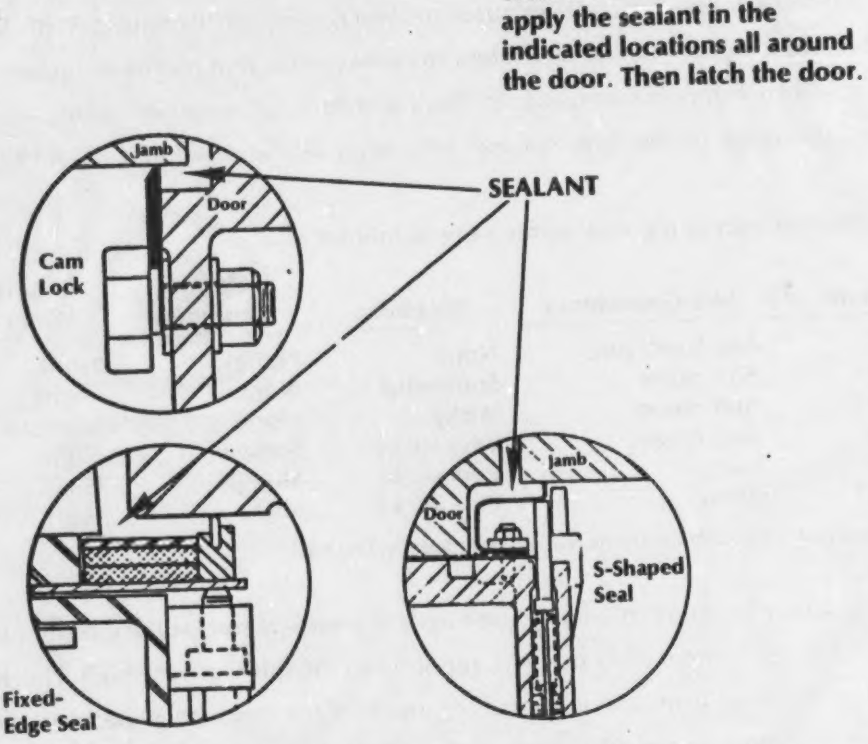

With the door off the oven, apply the sealant in the indicated locations all around the door. Then latch the door.
SEALANT
Jamb
Door
Cam Lock
Fixed-Edge Seal
Jamb
Door
S-Shaped Seal

FIGURE IV-8. ILLUSTRATION OF THE CONCEPT OF "INBOARD LUTING", I.E., THE APPLICATION OF LUTING MATERIAL IN THE GAS PASSAGE OF EXISTING EQUIPMENT

would be inadvertently "missed" on some doors. Without a backup-sealing system, any errors in sealant application would become painfully apparent only after the coal had entered the oven, i.e., the emissions from a poorly luted door could be huge and would probably represent a serious fire hazard in terms of probable fire damage to nearby end-closure elements. The concept of using sealants inside the gas passage areas of existing seals gives the sealant sealing system a backup metal-to-metal sealing system and would eliminate one of the reservations we had about sealant systems.

Summary of the Follow-On Laboratory Tests

Variations in Water Content in Sealants

A few experiments were conducted to learn the effect of water content on the unsupported adherence of the most promising sealant mix when the mix was applied to a hot, vertical steel surface. The mix consisted of 1 part of 1.68-mm (12-mesh) fireclay (Cedar Heights

Clay Company), 1 part coke breeze, and 8 volume percent corn starch. Batches of about 1 liter (about 1 quart) were dry mulled for 15 minutes and wet mulled for 10 minutes. With 37 volume percent water, the consistency was equivalent to earlier mixes that had been prepared with a similar clay (used by Koppers Company, St. Paul) and 28 volume percent water. As with the earlier mixes, shrinkage of the new mix was zero when it was dried in a 530 K (500 F) steel channel.

Some characteristics of the new mixes were as follows:

Water Content, v/o	**Mix Consistency**	**Stickiness**	**Slump Tendency**	**Surface Water Sheen**
37	Mod. soft putty	None	None	None
43	Soft putty	Somewhat	None	Slight
49	Stiff cream	Sticky	None	Moderate
54	Soft cream	Very sticky	Somewhat	High
58	Slimy	Very sticky	Slumps	High
KSPL*	Slimy	Very sticky	Slight	High

*Koppers Company, St. Paul loam consisting of clay, coke breeze, and coal.

Samples of about 16 cm^3 (1 in.^{3}) were flung against a vertical steel surface heated to 420 K (300 F). Above a water content of 49 percent, rebound of the mix was very high. The adhered splats ranged in thickness from about 6 mm (1/4 inch) for the mix with 37 percent water to 2 mm (1/16 inch) for those above 40 percent water. All of the splats adhered for 6 minutes at which time they were dry and the test was terminated.

When flung against the steel surface at 530 K (500 F), the results were as follows:

	Splat Thickness		
Water Content, v/o	**mm**	**inch**	**Adherence, minute**
37	6.35	1/4	1/4
43	3.18	1/8	1
49	3.18	1/8	1-1/2
54	1.59	1/16	7 Splat dry,
58	1.59	1/16	7 test terminated
KSPL	3.18	1/8	7

Application of a 13-mm-thick (1/2-inch-thick) layer to the steel plate at 530 K (500 F) was attempted. The adherence of mixes with a water content of up to 54 percent ranged from nil to about 1 minute. The mix with 58 percent water and Koppers' loam separated from the steel surface when the second thin layer was applied to build up the thickness. All of the mixes were adherent when applied as a single 3-mm-thick (1/8-inch-thick) layer. Good adherence persisted up to 15 minutes at which time the test was terminated.

The results of the above experiments suggest that the thinner mixes (high water content) had better adherence to a vertical, heated steel surface. Additional study is recommended.

Application of the mixes by flinging resulted in excessive rebound from the steel surface. Rebound was greater and adherence was poorer when the mixes were flung against the steel surface at the higher temperature, 530 K (500 F). Building up a thick layer by flinging may result in premature release of the initial layer. In the event that "thick" layers prove to be a problem under production conditions, the gas passages can be "filled" to lower the thickness (and material requirements) as shown in Figure IV-9. There are other options or alternatives that can be explored.

Adherence was good for all of the mixes when they were applied as a thick layer to the steel surface heated to 420 K (300 F). Adherence of thick layers was poor when the mixes were applied to the steel surface heated to 530 K (500 F). However, 3-mm (1/8-inch) layers were very adherent. This suggests that the mixes may be applied as adherent thick layers to a steel surface at 530 K (500 F) if the mixes are pressed so that they retain intimate contact with the steel until the mix interface loses its bulk water. Steam generated at the interface is suspected as the cause for poor adherence. *Additional research would be required prior to any demonstration effort.*

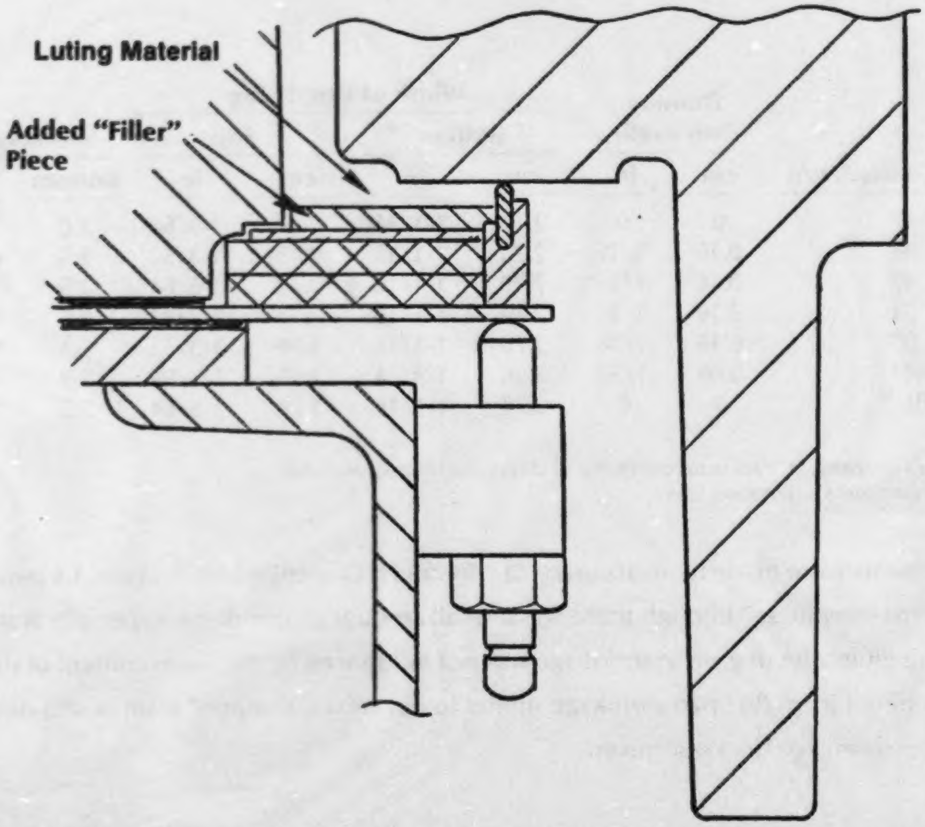


FIGURE IV-9. EXISTING SEALS CAN BE EQUIPPED WITH A "FILLER" SECTION TO MINIMIZE THE AMOUNT OF MATERIAL USED IN INBOARD LUTING

For a given dwell period on the hot steel surface, plasticity of our mix was higher than that of Kopper's loam. Comparison with Koppers' loam showed the need and effectiveness of corn starch in our mix in promoting prolonged plasticity when the mix was in contact with a hot surface.

Effect of Water Content on Sealant Shrinkage

The 1-liter (1-quart) batches which were prepared for evaluating the effect of water content on adherence to a heated, vertical steel surface, were also used to evaluate the effect on shrinkage during drying.

A steel channel at 530 K (500 F) was filled with the loam and pressed flat with a spatula. The channel was 2.86 cm (11-1/8 inches) deep, 2.82 cm (1-7/64 inches) across the top, and 2.74 cm (1-5/64 inches) across the bottom. Temporary steel end dams (coated with silicone spray; removed after filling the channel) made a cavity 3.18 cm (1-1/4 inches) long. The dry sealant plugs were measured after a dwell of 3/4 hour in the heated channel with the following results:

	Doming (top swell)		Width of Dried Plug				Shrinkage, %	
			Bottom		Top			
Water Content, v/o	**cm**	**in.**	**cm**	**in.**	**cm**	**in.**	**Bottom**	**Top**
37	0	0	2.70	1-1/16	2.74	1-5/64	1.5	1.4
43	0.16	1/16	2.70	1-1/16	2.78	1-3/32	1.5	0.02
49	0.16	1/16	2.70	1-1/16	2.74	1-5/64	1.5	1.4
54	0.16	1/16	2.70	1-1/16	2.78	1-3/32	1.5	0.02
58	0.16	1/16	2.70	1-1/16	2.78	1-3/32	1.5	0.02
KSPL[a]	0.08	1/32	2.66	1-3/64	2.66	1-3/64	2.9	4.3
BL[b]	0	0	2.70	1-1/16	2.74	1-5/64	1.5	1.4

(a) Koppers Company, St. Paul loam consisting of clay, coke breeze, and coal.
(b) Bethlehem Steel Corporation loam.

Measurements were made to an accuracy of 0.04 cm (1/64 inch) which is about 1.5 percent of the width of the plugs. Although there was a small amount of shrinkage, especially at the bottom of the plugs, the degree of shrinkage was not influenced by the water content of the mixes. Bethlehem's loam (BL) had shrinkage similar to our mixes. Koppers' loam (KSPL) definitely had higher shrinkage than our mixes.

Subjective judgment of the characteristics of the mixes was as follows:

Water Content, v/o	Mix Consistency	Sag Tendency	Surface Water Sheen	Stickiness
37	Very stiff putty	None	None	None
43	Soft putty	None	Slight	Moderate
49	Stiff cream	None	Moderate	Sticky
54	Soft cream	Slight	High	Very sticky
58	Slimy	Very	Very high	Very sticky
KSPL[(a)]	Slimy	Moderate	Very high	Very sticky
BL[(b)]	Stiff cream	None	Moderate	Moderate

(a) Koppers Company, St. Paul loam consisting of clay, coke breeze, and coal.
(b) Bethlehem Steel Corporation loam.

Overall, the characteristics of KSPL most closely matched our mix containing 58 volume percent water; BL most closely matched our mix containing 49 volume percent.

Comments. The results were considered encouraging enough to complete a feasibility/costs/benefits analysis for Task IV. In any development/demonstration of inboard luting, it will be necessary to develop means of applying thick deposits of luting material. Development and demonstration of inboard luting was not included in our original proposal for a follow-on project.

Preliminary Evaluation of the Possibility of Cracking Cast-Iron Jambs as a Result of Using Wet Sealants

Gray cast iron jambs are usually replaced only because of crack formation, in some instances, after years (up to 20 years) of service. The number of jambs replaced per year because of cracking is a small percent of the total in service. Battelle researchers have examined jambs that were partly cracked and noted that, in all cases examined, the crack was extending inward (horizontally) starting from the outboard edge of the jamb web. The failure (cracking) of cast iron is almost always in tension. Due to the temperature gradients at jambs, it is to be expected that the outer edge of the jamb web is normally under some tension.

Because of the existing jamb-cracking problem, coke-plant superintendents are wary of procedures that chill or thermally shock their cast iron jambs. In addition, they are wary of procedures that would appear to insulate the exposed portion of jambs. An example of major chilling of jambs is the rapid quenching that occurs during heavy rainstorms. A minor jamb chilling effect results from the practice of using water hoses to put out fires at poorly fitting coke-oven doors. An example that includes both chilling and insulating might occur upon compressing a wet sealant against warm jambs. The water contained in the sealant will cool the surface of the jamb. After the sealant has dried, it would tend to insulate a part of the jamb surface.

As part of the sealant-testing task, it was decided to find out to what degree the application of water-tempered sealant would change the stress level at the surface of the seal-mating portion of jambs. To approach these conditions, sealant was rapidly applied to the top web of the cross piece of the heated jamb in the physical model. This location was chosen because it had the desired accessibility and the required surface thermocouples and strain gages. The data obtained indicated that in about 1 minute following application of the sealant, the jamb surface temperature had dropped to a low of 430 K (310 F) from the original steady state temperature of 520 K (470 F). Following the period of flash cooling, the sealant dried slowly and the jamb temperature returned to 520 K (470 F) in 30 minutes. The maximum temperature change then was 90 K (160 F). Temperature-compensated strain gage readings taken over the maximum temperature-differential period indicated that there had been a short-period increase in tensile stress of 11.7 MPa (1700 psi). As the temperature of the jamb surface returned to the original temperature, the surface stress level also returned to the original level.

A tensile stress spike of about 11.7 MPa (1700 psi) for every application of wet sealant is considered to be a very minor increase in tension *at the seal-mating surface*. It was concluded that this periodic minor straining should not result in the development of cracked jambs. Stated another way, it is not expected that the application of wet sealant to the seal-mating surface will initiate cracks starting at this location. This is a judgment conclusion based upon the reasoning that the seal-mating portion of the jamb is near the neutral plane of the jamb; i.e., the seal-mating surface is normally at a low service-stress level. The work of Kattus and McPherson* in thermal shocking mechanically loaded samples of metal indicated that the number of cycles to cracking was a function of the level of the bending stress on the samples. The higher the bending load on steel and cast iron samples, the fewer the number of quenching cycles [700 to 300 K in 15 seconds (800 F to 75 F in 15 seconds)], and vice versa. At low levels of bending stress, notched samples of cast iron would either not crack or would require a very large number of cycles to initiate cracking. All coke-oven jambs are hotter on the back side. Under conditions where these jambs are constrained (actual amount of inward jamb bowing is less than the bowing that would occur naturally as a result of the thermal gradient), the backside jamb *surface* is under maximum compression and the exposed outboard web *surface* is under maximum tension. The seal-mating surface is located between these two extremes and is near the cross-over point between tension and compression (the neutral plane) and it is, therefore, only under some low service stress (mild compression or mild tension). It is expected that mild chilling of a seal-mating surface that is not at a high stress level will not result in a crack formation.

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*Kattus, J. R., and McPherson, B., "Properties of Cast Iron at Elevated Temperatures", ASTM STP No. 248.

If the coke-producing industry accepts the concept of inboard luting and proceeds with a program of development and implementation; it may be advisable to measure the service stress level on operating jambs to verify our judgmental conclusion.

It is probable that the implementation of inboard luting will raise the average temperature of jambs, but by only a small amount. The portion of the jamb (underneath the seal) that would be insulated by the dried luting material is not now in a good position to lose heat. The degree of temperature rise is, therefore, expected to be small, but should be determined and evaluated in any demonstration project.

Overall Summary of the Laboratory Research and Field Tests

The results of the laboratory research and field tests lead to the following overview:

(1) The results of all of the laboratory and field work are regarded as being favorable and in line with our objectives. Our interpretation is that inboard luting has the potential of being developed into an alternative sealing method. However, the work that was completed can only be considered as "scoping research" inasmuch as various details that could improve/optimize the results were not evaluated. Further work was held in abeyance because (a) we had reached the end of the funds allotted to this part of the project and (b) we need to learn the judgments of our Sponsors (EPA/AISI). Additional optimizing research/development in sealant characteristics would be required if any organization elects to carry on with this approach. As one general example, clay from only one deposit was evaluated, and no attempt was made to control the mesh size of the materials used in preparing the mixtures. It is probable that the introduction of some portion of finely ground coke breeze would lower the required amount of water.

(2) In the approach being recommended, the sealant would be applied (mounded) into the gas passage area between the existing metal seal and the door plug. This would, in most instances result in a wider cross section of sealant than the 25-mm (1-inch) width that was tested in the field. It is judged that the emission tightness exhibited by a 25-mm-wide (1-inch-wide) layer of sealant containing 33 volume percent water will be duplicated by a wider cross section of sealant having a

higher water content. The application of sealant into the gas passage of the door rather than application on the jamb is expected to have advantages because this area is normally cooler than the jamb, especially after the door has been off the oven for a normal period.

(3) The application of sealant onto the heated jamb of the physical model of the door/jamb indicated that the tension in the surface layer of the jamb in the sealant area was momentarily increased by about 11.7 MPa (1700 psi). Overall, the contact of the wet and slowly drying sealant to a heated jamb is a mild cooling effect as compared with a rainstorm. On the other hand, the application of the sealant could be presented as a mild and short sprinkle of rain occurring every 16 to 24 hours. It is judged that the use of sealant sealing will cause cracking only if the jamb surface is already at a high level of tension. On some jambs, it is estimated that there can be high tension only on the outboard edge of the web of the jamb. The sealant-mating portion of the jamb, however, is closer to what would normally be the compression side of the jamb. From this general evaluation, we expect that the use of a sealant will not cause jambs to crack. This is not, however, a warranty; additional research would be advisable.

(4) Overall, it was judged that sufficient progress has been made to complete a feasibility/costs/benefits analysis on sealants. *In this regard it should be noted that the inboard luting approach has the potential of eliminating the need for manual cleaning of both the jamb and the gas passage on doors.*

Feasibility Analysis

In the Work Plan dealing with this project, it was stated that a feasibility/costs/benefits analysis of sealant procedures would be completed if there had been demonstrable progress in this research project. We feel that this progress has been demonstrated short of development/demonstration efforts at coke plants. This portion of the report deals with an analysis of the overall potential of use of sealants.

As it stands now, it is judged that the approach is technically feasible. It has a basic attraction in that it appears that it could be implemented rapidly. Emission control on existing older ovens (with the use of sealants within the existing metal seals) would be significantly better than continued operation with the existing metal seals. Short of a demonstration project, the pertinent questions at this time are:

(1) Will the sealant method give better emission control (at end closures) than the upgraded metal seals that are being developed?

(2) What are the relative costs of sealant sealing and upgraded metal seals?

(3) For what period of time will upgraded metal seals give acceptable emission-control performance?

(4) Are there coke plants where the sealant approach might be readily accepted (and developed and evaluated) because of special circumstances?

Definitive answers to Questions 1, 2, and 3 require the testing of both approaches (sealants and improved metal seals) in comparable situations and the development of a consensus decision based on overall merit. On the other hand, one evaluation approach that can be taken is to assume that a sealant will match upgraded metal seals in emission-control performance. This approach shifts the emphasis to developing an answer to Question 2. An attempt was made to answer this question in a definitive way, but we encountered an unknown or a yet-to-be-established cost element. This cost element is whether or not there is a need to employ additional workers just to apply sealants on doors.

As background to the unknown cost element, it may be helpful to know that every coke battery has two working sides and has at least one "benchman" worker per side of the battery, per shift. There are at least 2 benchmen per battery per shift, or a total of 8 for the 4-turn (24-hour per day) coke battery operation. The duties of these individual workers are listed below (with comments):

Duties	Comments
(1) Shovel coke spillage and clean the bench.	(1) Some batteries have a large amount of spillage and others do not.
(2) Manually clean the jamb while the door is off the oven.	(2) Where batteries do not have jamb-cleaning machinery (and this is all batteries less than 5 meters tall), this is a difficult task. Performance of this task varies from "not done" to a "reasonable amount of effort". Where the work load (defined later) is heavy at a particular battery, this task is often omitted or neglected.
(3) Manually remove at least some of the tar and carbon that collected in the gas-passage area on the door.	(3) This task has many of the difficulties (and worker resistance) associated with jamb cleaning. In many instances, this work is done only periodically (once a week). This is acceptable from the sealing-performance viewpoint. So long as carbon is not allowed to build up to the point where it interferes with the door fitting into the oven or interfering with the seal mating with the jamb, emission control is not affected. However, allowing the buildup of tar (which converts to adhered carbon) only makes the cleaning job more difficult when the carbon must be removed. Some companies are developing periodic high-pressure, water-jet cleaning of the gas-passage area.

Duties	Comments
(4) Chip out the hard carbon that builds up on the oven sill below the door.	(4) The rate of carbon buildup differs among plants. Need for chipping can be "seldom".
(5) Assist in bottom latching of doors when problems occur.	(5) The need for this assisting duty depends on the condition and age of the equipment.

At the 6-meter batteries, machinery has been installed to eliminate Duties 2 and 3 above. At some locations, the benchman is still needed to "touch up" the cleaning of the jamb when the machinery is awaiting adjustments.

In the recommended approach of applying sealant inboard of the existing seals, it is expected (but not proven) that one application per cycle will eliminate the need for the arduous duties of manually cleaning the jamb and door (Duties 2 and 3 in the above listing). Because sealant cannot be applied manually (as is done in outboard luting), it is assumed that this operation will be at least partly mechanized. In one approach, the worker would coat the door areas by using a version of a pneumatic spray gun. It would be necessary to install an elevator or stairs arrangement that would allow the worker to approach his work areas near the top of the doors.

At least in theory, it would seem appropriate to substitute/exchange an equipment-supported, inboard-luting duty for the two manual (and difficult) cleaning duties. Theory may be appropriate at some coke plants where there are relatively few ovens per battery and where the coking rate is low. On a 50-oven battery making 24-hour coke, the number of door openings per side is an average of 17 per shift, or about a half hour apart. On the other hand, at a 90-oven battery making 16-hour coke, the average number of door openings per side is about 45 per shift or about one every 10 minutes. In most instances, the door-removal rate is lower than the average time (i.e., faster operation) because of rest breaks and the need to "pick up" the time lost in operating delays. There is, therefore, a rather wide range of working-rate or work load for bench workers at coke batteries. As understood by Battelle researchers, the work load on the bench is the subject of negotiation between the company and the local union representatives. Coke-plant supervision and personnel did not feel that they were in a position to predict the outcome of negotiations dealing with the possible introduction of sealants.

As might be expected, the cost of using sealants will be the highest where additional workers are required. Conversely, the lowest cost will exist where an agreement is reached that the existing benchmen would apply the sealant in exchange for eliminating the duties of manual cleaning of jambs and doors. Because all upgraded sealing approaches represent an increase in cost, the most acceptable emission-control solution will be that with the highest relationship of performance to cost. The cost aspects of the use of sealants are considered in the following section.

Cost of Sealant Approach Including Additional Benchmen

In some instances, it may be necessary to consider the addition of a benchman to apply sealants. A cost approximation for this situation is as follows:

Assumptions

(1) Adding a helper benchman represents adding 8 additional workers per battery. Battery operation is a 4-shift-per-week system and there are two sides to a battery. It is judged that an additional day-turn man would be required to prepare the sealant. The total increase in crew size would then be 9 workers per battery.

(2) Cost per worker added will average about $20,000 per year, including all employment costs. Lutermen sealing doors with outboard luting (slow coking) are presently paid about $16,000 per year (gross), including incentive pay. Employment costs approach 30 percent or more. The additional labor cost for inboard luting workers would be 9 × $20,000, or $180,000 per year.

(3) In late 1976, the selling price of a complete mixing, pumping, and pneumatic spraying package was $15,000. This unit will deliver 0.85 cubic meters per hour (30 cubic feet per hour). A heavy application of sealant at any one door could take as little as 20 seconds of time depending upon positioning of the worker. Two spraying systems are required per battery. Including installation and winterizing, the installed cost for both units would total about $60,000 or more. The cost of equipment or equipment modifications to allow the worker to reach the upper parts of the door (while it is off the oven) may cost $40,000 installed. Total installed cost is taken as $100,000.

(4) The coke battery being considered has 50 ovens and produces 290,000 tonnes(320,000 net tons) of coke in a high-demand year.

(5) The cost of the sealant material is about 10 cents per door closing, or about $5,000 per year on the above battery.

(6) Door-seal maintenance costs are lowered by $20,000 per year. Coke-producing companies report a savings in maintenance costs and possibly an increase in door-plug life in comparing batteries having luted doors with those having metal

seals. These are, however, only generalizations inasmuch as no attempt has been made by these companies to pinpoint the actual amount of savings. The above figure is, therefore, a guess—it might be on the low side or it could be on the high side.

(7) The after-tax cost of capital is taken as 10 percent. This is a variable depending somewhat on the profitability of the company and the industry and may, for this industry, be a low figure.

(8) The depreciation life of the new equipment (installation costs included) is taken as 10 years with no salvage expected. Straight-line depreciation is used.

(9) For purposes of illustration only a simple approach is used. No consideration, therefore, was given to (a) rate of inflation, (b) time value of money*, or (c) the effect of decreases in production rate during low-demand periods.

Case A: Equipment Installed, 9 Additional Workers Hired

Yearly Expenses:

(a) Increased labor costs (including cost of employment)	$180,000
(b) Sealant cost	5,500
(c) Cost of capital (10 percent of $100,000)	10,000
(d) Depreciation expense (10 percent of $100,000)	10,000
	$205,500
Savings on metal-seal maintenance	$30,000
Estimated net cost per year	$175,500
Estimated cost per ton of coke	61¢/tonne of coke (55¢/ton) of coke

For this added cost per year, and using the same simplified expense format, the coke plant could invest up to $725,000 for upgraded metal seals. This assumes that the saving on seal maintenance is lost. An investment of $725,000 presents an investment of $7,250 per door over a period of 10 years. Investment credits and consideration of the time value of money would tend to increase this allotment.

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*This is a valid approximation because the investment cost is low relative to total cost.

Case B: Equipment Installed, One Additional Worker Hired to Prepare Sealant

Yearly Expenses:

(a) Increased labor cost	$20,000
(b) Sealant cost	5,500
(c) Cost of capital	10,000
(d) Depreciation expense	10,000
	$45,500
Savings on metal-seal maintenance	$30,000
Estimated net cost per year	$15,500
Estimated cost per ton of coke	5.5¢/tonne of coke (5¢/ton) of coke

In this case, the savings on maintenance cost is greater than the sum of the cost of the additional labor and the cost of sealant materials. Considering that it is probable that the cost savings would be lost in switching to upgraded metal seals, *in this instance*, sealant would have a more favorable performance/cost ratio than upgraded metal seals.

The purpose of the foregoing examples was to illustrate that, to some degree, the acceptance of sealants (inboard luting) will depend upon:

(a) Whether or not there is a need for additional benchside workers,

(b) Whether or not sealant application can be automated to the degree that additional benchside workers are not required at high-load plants, and

(c) The attitude of the personnel and their union representation.

Because of the low profitability of the steel industry as a whole*, it is considered doubtful that the coke-producing segment of this industry will give any consideration to adding additional benchmen to apply sealants.

Question No. 4 in the introductory portion of this section was "Are there coke plants where the sealant approach might be readily accepted (and developed and evaluated) because of special circumstances?" We believe that the answer is "yes", because there must be some coke batteries that:

(a) Need entire new end closures for continued operation, or

(b) Have a limited life left in the battery, but there is a present or expected future need to keep them operating. This could include operating the old battery until the decision and the building of a new battery have been completed, or

(c) Are low-speed batteries such that the work load on the bench is not high.

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*One reference is *Business Week*, January 9, 1978.

It appears that the use of a sealant could keep warped end closures operating under good emission control. In addition, it is conjectured that:

(a) Pneumatic luting of ovens that are presently being manually luted could improve their emission-control performance, and

(b) The pumping equipment recommended for this overall approach probably can be modified or augmented to become a superior (more labor-efficient) equipment for use in patching behind jambs. In this new application, refractory mortars or insulating mortars could be substituted for the low-cost mixtures recommended for inboard and outboard luting.

Conclusions

The following conclusions have been drawn:

(1) Acceptance of the use of sealants (if this method can be developed and implemented) will depend upon whether it is possible to introduce the use of sealant applying equipment without materially increasing the number of workers on the bench.

(2) There are thought to be coke plants operating under special circumstances such that the plants would have a special need for the use of sealants.

Recommendations

The following recommendations are made:

(1) The Sponsors should give consideration to the development, testing, and demonstration of inboard luting. The coke-producing industry (members of the AISI and companies belonging to other associations) should be polled to determine which companies are interested in the inboard luting approach.

(2) Individual companies should not attempt a trial-and-error approach to inboard luting without the support of additional laboratory work. The interested companies should pool their resources to give inboard luting a strong, technically oriented development effort. This effort should include (a) testing to determine whether compressing wet sealants against heated jambs will or will not result in cracking of gray iron jambs, and (b) development of sealants and application methods that will result in the adhered thickness required.